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Report

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# Salt Repository Synthesis Data of Non-Delaware Basin and International Programs for the Storage/Disposal of Nuclear Waste

## Fuel Cycle Research & Development

**FCT Quality Assurance Program Document**

# Appendix E
# FCT Document Cover Sheet

| | |
|---|---|
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**This Deliverable was subjected to:**

| | |
|---|---|
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| **Review Documentation Provided** | **Review Documentation Provided** |
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# LOS ALAMOS NATIONAL LABORATORY

# Salt Repository Synthesis Data of Non-Delaware Basin and International Programs for the Storage/Disposal of Nuclear Waste

## October 2012
## LCO-SDI-002, Rev 0

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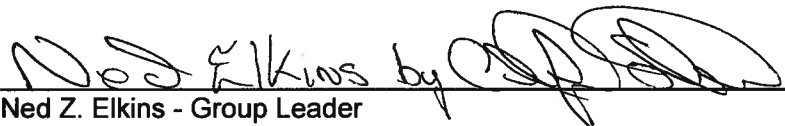
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## HISTORY OF REVISION

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# ACRONYMS

| Acronym | Description |
| --- | --- |
| ADDIGAS | Advective and Diffusive Gas Transport in Rock Salt Formations |
| BAMBUS | Backfill and Material Behavior in Underground Salt Repositories |
| bgs | Below Ground Surface |
| CBFO | Carlsbad Field Office |
| Cp | Heat Capacity |
| BGR | [German] Federal Institute for Geosciences and Natural Resources |
| BRC | Blue Ribbon Commission |
| Ci | Curie |
| cm | centimeter |
| °C | Degrees Centigrade |
| °F | Degrees Fahrenheit |
| °K | Degrees Kelvin |
| ft | feet |
| DEBORA | Development of Seals for HLW Disposal Boreholes |
| DHLW | Defense High Level Waste |
| DOE | Department of Energy |
| EDZ | Excavation Disturbed Zone |
| ERAM | Endlager für radioaktive Abfälle Morsleben |
| EKRA | Expertengruppe Entsorgungskonzepte für radioaktive Abfälle |
| GRS | Gesellschaft für Anlagen- und Reaktorsicherheit |
| HLW | High-Level Waste |
| in | inch |
| L | Litre |
| km | kilometer |
| kW | kilowatt |
| m | meter |
| mL | milliliter |
| mm | millimeter |
| molar | molar |
| MPa | Mega pascal |
| NDA | Nuclear Decommissioning Authority |
| ONWI | Office of Nuclear Waste Isolation |
| PBq | Peta becquerel |
| PSV | Project Salt Vault |
| rad | radiation absorbed dose |
| SCP | Site Characterization Plan |
| SDI | Salt Disposal Investigations |
| SDDI | Salt Defense Disposal Investigations |
| SITED | Salt Investigations Technical Expansive Database |

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| Acronym | Description |
|---------|-------------|
| SNL | Spent Nuclear Fuel |
| SNL | Sandia National Laboratories |
| SWCT | Simulated Waste Container Test |
| TSDE | Thermal Simulation of Drift Emplacement |
| THMC | Thermal, Hydrologic, Mechanical, and Chemical |
| WIPP | Waste Isolation Pilot Plant |

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# 1.  DESCRIPTION OF PURPOSE

This report was developed in accordance with the LANL-Carlsbad Operations quality assurance program, specifically procedure LCO-QP6-1, *Controlled Document Development, Change and Revision* (LANL-CO, 2012)*.* This deliverable is part of the scope developed for a salt research and development study completed on March 23, 2012 and agreed upon by the U.S. Department of Energy Offices of Nuclear Energy and Environmental Management.

Several decades of data related to salt and its performance as a storage medium for nuclear waste exist throughout the United States and the international scientific literature. These data address the bedded Salado formation in the Delaware Basin, other U.S. domal salt locations, and domal salt abroad. However, this body of knowledge remains incomplete regarding research and documentation of thermal effects in bedded and domal salt. In fiscal year 2012, the U.S. Department of Energy's (DOE) Used Fuel Disposition campaign funded an activity to compile available existing data in a format that allows ready access to important historical research that has already been performed on salt both from U.S. and international programs. The web-based electronic database developed for this organizational function is titled the Salt Investigations Technical Expansive Database (SITED).  The database is hosted from a Sandia National Laboratories (SNL) webserver (https://sited.sandia.gov/sited) that has limited read/write access to authorized personnel. Furthermore, an assessment of this existing salt data was funded to support the proposed research program described in the referenced Salt Defense Disposal Investigations (SDDI) conceptual plan (DOE, 2012) and Salt Disposal Investigations (SDI) proposal (DOE, 2011).

The purpose of the report is to summarize thermal salt data from testing programs that were implemented at non-Delaware Basin salt sites (e.g. Project Salt Vault, Avery Island) and from international testing programs (e.g. Germany). This report will contain a synthesis of the available literature compiled in SITED and assess the relevance of the studies associated with nuclear waste disposal in bedded and domal salt. A determination whether there is a continued need for research into the potential performance of a repository for heat-generating waste in bedded salt will be stated. These assessments will be conducted in comparison to an in-drift disposal concept in bedded salt outlined by the DOE in the *Conceptual Plan for Salt Defense Disposal Investigations for the Disposal of DOE-EM Managed Wastes* (DOE 2012).

In June 2011, *A Proposal for Salt Disposal Investigations with a Field Scale Heater Test at WIPP* (DOE 2011), was completed that outlined a science-based scope of work for a defined scope of research (laboratory work and modeling efforts) intended to establish the foundation for a proof-of-principle field test for disposal of heat-generating nuclear waste. The SDI proposal was based upon an alcove emplacement strategy with a geometry that allowed for a straightforward way to distribute hot waste packages to distribute the heat load.

While the rationale for the SDI project applies to civilian and defense wastes, the SDI proposal does not specifically address information needed for the DOE Office of Environmental Management (EM) to make important early decisions on disposal of the defense high-level waste (DHLW) and Spent Nuclear Fuel (SNF) that it manages. There is merit in an approach that covers a range of thermal loads that, in total, covers the entire spectrum of heat-emitting wastes in need of disposal, rather than focusing only on the very high heat loads. To address the needs explicitly associated with disposal of these DOE-EM managed wastes, a conceptual plan, was completed (DOE 2012) which provides an overview of an in-drift emplacement strategy and corresponding test program based on disposal canisters laid on the drift floor and

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covered with crushed salt (run-of-mine) backfill for shielding. This test program is to demonstrate confirmation of certain principles in salt and to demonstrate an in-drift disposal concept, providing confidence in and confirmation of the concept.

This report will conclude the relevance of the studies from non-Delaware Basin and international salt sites to the waste disposal concept and proposed test programs described above. Based on this relevance, the need for these proposed testing programs will be either confirmed or voided.

# 2.  OVERVIEW

The Blue Ribbon Commission (BRC) on America's Nuclear Future charter directs the Commission to provide advice, evaluate alternatives, and make recommendations for a new plan to manage the back end of the nuclear fuel cycle in the United States. The BRC concludes that disposal is needed and that deep geologic disposal is the scientifically preferred approach. This same conclusion was reached by every expert panel that has looked at the issue and by every other country that is pursuing a nuclear waste management program (BRC, 2012). The BRC further states that the "United States should undertake an integrated nuclear waste management program that leads to the timely development of one or more permanent deep geological facilities for the safe disposal of spent fuel and high-level nuclear waste." The BRC goes on to state that while several options for disposing of spent fuel and high-level nuclear waste have been considered in the United States and elsewhere, international scientific consensus clearly endorses the conclusion that *deep geological disposal is the most promising and accepted method currently available for safely isolating spent fuel and high-level radioactive wastes from the environment for very long periods of time.*

Almost all concepts for disposal of radioactive waste from the civilian use of nuclear energy were formulated at a relatively early stage (mainly in the 1950s). In general, the international community endorsed geologic disposal, which is defined as the strategy of disposal of waste in deep geological formations of the continental earth's crust. Typically, arguments in favor of geologic disposal are generally well accepted. However, reservations were expressed regarding whether or not the long-term safety of a repository could be sufficiently ensured based on the means and methods available today. Therefore, over the last few years some countries have been studying and even pursuing reversibility strategies and concepts, which incorporate sequential monitoring and control for retrieval of waste.

Evaluation of the different waste management concepts has led Expertengruppe Entsorgungskonzepte für radioaktive Abfälle (EKRA) to reach the following conclusions (Wildi et al., 2000):

1. Interim storage facilities do not meet the key requirement for long-term safety.
2. Surface-based facilities and deep indefinite storage facilities also fail to meet the criteria for long-term safety.
3. Geological disposal is the only method for disposing of radioactive waste which meets the long-term safety criterion (up to more than 100,000 years).
4. Social expectations in terms of waste disposal are oriented towards the principle of reversibility. EKRA has therefore developed the concept of monitored long-term geological disposal, which combines elements of disposal and reversibility.
5. With regard to safety and the procedures to be followed during the transition from *monitored long-term* geological disposal to geological disposal, there are still open questions that need to be addressed and answered for this transition.

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The Nuclear Decommissioning Authority/Radioactive Waste Management Directorate (NDA/RWMD) discusses their plans for managing geological disposal of high activity radioactive wastes (NDA, 2010). In their report the NDA provides information on the steps they believe will be required for successful implementation of geological disposal. The United Kingdom believes they have suitable geology to host a geological disposal facility. From their preparatory work, three broad (generic) host-rock types were considered: higher strength rocks, lower strength sedimentary rocks, and evaporites. The higher strength rocks, for example granite, generally have a very low permeability to water flow so that any water flow that does occur is in open cracks or fractures that have formed in the rock mass. Granitic rock masses are planned to be used in Finland and Sweden at the sites chosen for their geological disposal facilities for spent nuclear fuel. Lower strength sedimentary rocks are generally physically uniform and any flow of water occurs through the overall rock mass. The Swiss Opalinus Clay geological disposal concept is designed for this type of rock. Evaporites (e.g., rock salt) may contain water that has been trapped within the crystals since they were formed, but in general evaporite sequences are isolated from water flow that could dissolve them.

The French disposal concept relies on the remarkable properties (retention capability, low permeability and homogeneity of the formation) of the various clays, which delay and mitigate the migration of the radioactive substances contained in the high-level, intermediate-level, low-level waste intended for deep underground disposal. The clay disposal concept intent is to delay radionuclide migration to the biosphere until their impact does not induce more risk than naturally-occurring radioactivity. Therefore, the French disposal concept relies heavily on the geology to provide the overall performance guarantee from the natural environment, while the actual disposal packages and structures are greatly simplified. The main role of packaging will be to delay any contact of the waste with the geological environment beyond the thermal phase, which is intended to spans a few centuries.

The German reference concept for the direct disposal of high-level waste (HLW) and spent fuel in rock salt also calls for deep (870 m or 2850 ft) geological disposal: with emplacement of HLW in boreholes and spent fuel casks in drifts with crushed salt backfill. They also have planned as part of their emplacement demonstration program a 10-year in situ heater experiment (Bollingerfehr et al., 2010).

# 3. DESCRIPTION OF SITES CONSIDERED

This section provides a summary of in situ field tests conducted from non-Delaware Basin and international salt sites. Each sub-section contain a brief summary of the investigations, a description of the disposal concept being tested, and a summary of the applicability of the specific testing program to the proposed SDI/SDDI testing program. Field tests to study the effects of HLW in bedded salt were initiated at an underground salt mine in Lyons, Kansas in 1965. By 1968, elevated-temperature HLW field experiments had begun at the Asse salt mine in Germany. In situ tests for brine migration resulting from heating were conducted at the Avery Island salt mine in Louisiana beginning in 1979. Soon after, an extensive suite of field thermal tests were initiated at the Waste Isolation Pilot Plant (WIPP) site near Carlsbad, New Mexico. Underground tests concentrated on heat dissipation and geomechanical response created by heat-generating elements placed in salt deposits. The SNL report, *Salt Disposal of Heat-Generating Nuclear Waste* (Hansen and Leigh, 2011), provides a concise summary of the history of salt disposal research for heat-generating nuclear waste. The following is a brief history from the SNL report of heated in situ testing in salt at locations outside the Delaware

Basin (i.e. non-WIPP) and each test is described in greater detail in the subsequent sub-sections.

Project Salt Vault (PSV): The first integrated field experiment for the disposal of HLW was performed by Oak Ridge National Laboratory in bedded salt near Lyons, Kansas between 1965 and 1969. The test was named Project Salt Vault and used one set of irradiated fuel assemblies from the Engineering Test Reactor at Idaho Falls as a source of intense radioactivity, while electrical heaters were placed in boreholes in the floor to simulate decay heat generation of HLW. The tests simulated the heat flowing into the base of the pillar from a room filled with waste with the primary focus on rock mechanics of floor, ceiling, and pillar deformation.

Avery Island: Brine migration tests were performed by RE/SPEC, Inc. for the Battelle Memorial Institute Office of Nuclear Waste Isolation in the Avery Island salt mine in Louisiana between 1979 and 1982. The migration of brine inclusions surrounding a heater borehole was studied on a macroscopic scale by investigating gross influences of thermal and stress conditions in situ. Field tests were augmented in the laboratory by microscopic observations of fluid inclusion migration within an imposed thermal gradient.

Asse Mine: Field experiments with electrical heaters were performed in the Asse salt mine in Germany in 1968 to investigate the near-field consequences of emplaced High Level Waste. Later repository options were investigated, including vertical borehole disposal of steel canisters and horizontal placement of steel casks surrounded with crushed-salt backfill. Emplacement of radioactive canisters was never conducted but a placement system was successfully tested without radioactive material, and the system was approved by the responsible mining authority. In all, three large-scale "heater" experiments were performed in the Asse mine, which yielded important data for the validation of material and computer models needed to assess the coupled long-term behavior of rock salt and crushed salt backfill in a salt repository.

A brine migration test in the Asse salt mine investigated the simultaneous effects of heat and radiation on salt between 1983 and 1985. This field experiment used Co-60 sources and heater arrays. The maximum temperature in the salt was 210°C.

Gorleben Germany: The Gorleben salt dome was investigated from 1979 until a moratorium beginning October 2000. All exploration activities were halted by the end of 2000, and a moratorium was imposed for up to 10 years. The moratorium ended in September 2010.

Morsleben: Also in Germany, the Morsleben salt dome was investigated. Several concepts for effective backfilling and sealing in salt were studied. Following studies and the successful demonstration of the disposal technologies used, the operational license was granted in 1981. Subsequent to the German reunification, the Federal Government of Germany took over the responsibility and the facility obtained the status of a federal repository and the disposal of waste was terminated in 1998.

## 3.1 PROJECT SALT VAULT: BEDDED SALT

Following the identification of salt as a potential host rock for radioactive wastes by the National Academy of Sciences in 1957 (NAS-NRC, 1957), a program was developed that included a series of in situ experiments to the understand further the response of salt when subjected to conditions similar to those expected in a nuclear waste repository. This program culminated in the mid-1970s with the successful completion of the PSV experiments as described below.

The Lyons mine of the Carey Salt Company, located in Rice County, Kansas, near the city of Lyons (Figure 3-1) was selected as the site for the Project Salt Vault (PSV) demonstration experiment. The mine was opened originally in 1890, and production terminated in 1948.  During this time period approximately 200 acres[1] were mined out. The salt was mined by the room and pillar method, with salt extraction varying from about 60 to 70%.  The floor of the mine lies a little over 1000 feet (ft) below land surface.
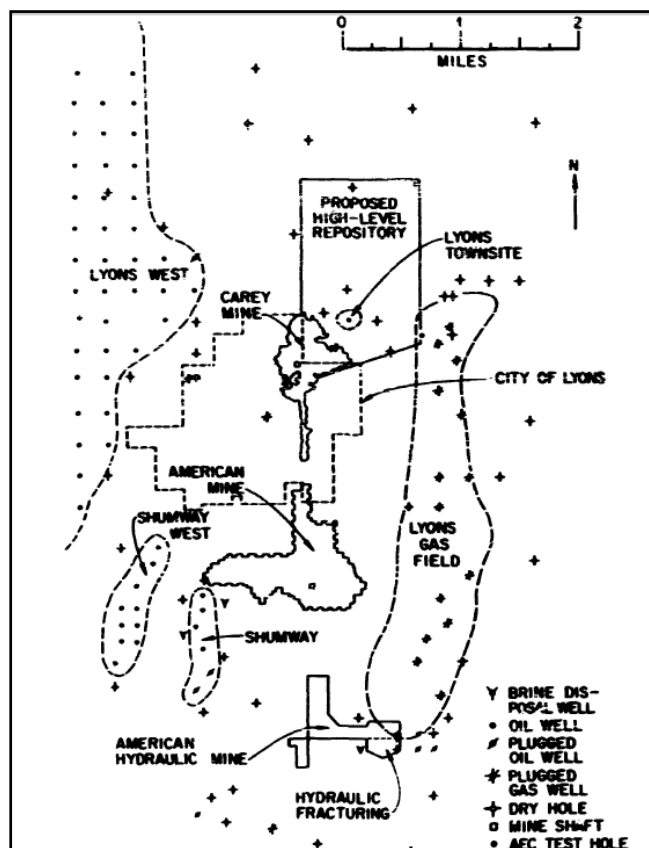


**Figure 3-1:  Location of Project Salt Vault (from Boch et al., 1972)**

The excavated horizon for the experiment was in the lower part of the Hutchinson salt member of the Wellington formation which is an integral part of the gently westward dipping Permian-Pennsylvanian sedimentary rocks that underlie much of Kansas. In general, the Hutchinson consists of salt, anhydrite, and shale, with salt being predominant throughout most of its extent in Kansas. At the Lyons mine, the Hutchinson salt member consists of about 300 feet of flat beds of salt, shale, and anhydrite, with salt comprising 60% of the sequence.

The engineering and scientific objectives of the PSV demonstration experiment were to: (1) demonstrate waste-handling equipment and techniques; (2) determine possible gross effects of radiation (up to $10^9$ rads [radiation absorbed dose]) on hole closure, floor uplift, salt shattering, temperature, etc. in an area where salt temperatures were in the range of 100 to 200°C; (3) determine possible radiolytic production of chlorine; and (4) collect information, especially on creep and plastic flow of salt at elevated temperatures, which

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[1] Measurement units in this report are stated in their original context.

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could be used later in the design of an actual disposal facility (Bradshaw et al., 1964; Bradshaw and McClain, 1971).

Project Salt Vault was the culmination of about ten years of study and testing by Oak Ridge National Laboratory that aimed at establishing the feasibility, safety, and techniques for disposing of high-level power reactor waste in natural salt formations.

### 3.1.1   SUMMARY OF INVESTIGATIONS

The experimental facilities at the mine (Figure 3-2) consisted of five newly excavated rooms (three 30 feet wide and two 40 feet wide) off a 30-foot-wide corridor at a level about 15 feet above the existing mine.  Two rooms contained circular arrays of seven boreholes (one in the center) in the floor, 5 feet apart and 12 feet deep. Fourteen irradiated fuel assemblies from the Experimental Test Reactor, two each in seven containers, were used to simulate actual solidified waste. These were placed in one of the arrays, while electrical heat only was applied to the other as a control to determine the combined effect of radiation and heat on the salt characteristics.  In the other two rooms, 22 electrical heaters (11 per room) spaced at 5 foot intervals in the floor were used to raise the temperature of a large quantity of salt in the central pillar to obtain information on its in situ deformational properties. The fifth room provided access to the lower end of a 20-inch (in) diameter shaft from the surface (AEC, 1971; Bradshaw and McClain, 1971).



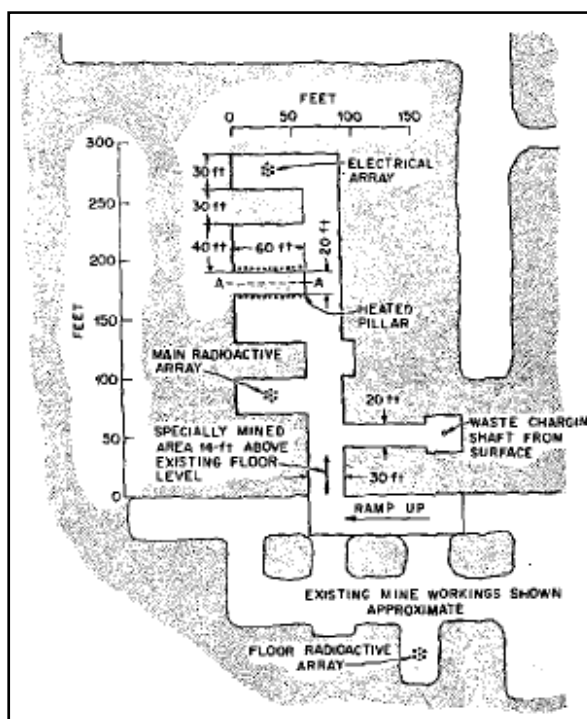**Figure 3-2:  Layout of the Mined Rooms for the PSV Experiments (from Bradshaw and McClain, 1971)**

During the 19-month course of the experiment, the average dose delivered to salt at the walls of the array holes was about $8 \times 10^8$ rads with a peak dose of $10^9$ rads. In spite of these high doses, there were no measurable radiolytic or structural effects in the salt. In addition to the radiation, a considerable quantity of heat (both decay and electrical) was deposited in the salt. Around the arrays a circular ellipsoidal volume of salt of about 1,400 $ft^3$ was heated between 100°C and 200°C. Under the heated pillar, a volume of salt of about 30,000 $ft^3$ was heated to temperatures greater than 60°C. These elevated temperatures produced rapid acceleration in the rate of closure of the mine because of the temperature dependence of the plastic properties of the salt and altered the pattern of deformation by the imposition of thermal stress (Culler, 1971).

## Temperature

In the arrays the total power input was nominally 10.5 kilowatts (kW), including both electrical and radioactive decay heat. Both the main radioactive and electrical control arrays (rooms 1 and 4) were started on November 15, 1965. When the fuel assembly cans were inserted, the electrical power was adjusted to maintain a constant total power input as the radioactive power decreased. On January 24, 1967, the power was increased about 40% to reach a peak salt temperature of about 200°C  The carbon steel modified pillar heater in room 2 was started on June 22, 1966, at a nominal power input of 3 kW and operated at this level until November 11, 1966. On November 14, 1966, all of the pillar heaters (22, including the modified heaters) were started at a nominal power input of 1.5 kW per heater (33 kW total). The wattmeter indicated that this average level was fairly well maintained until shutdown on October 9, 1967.

Comparison of the maximum temperatures in the horizontal plane achieved in the array rooms indicated that there was essentially no difference between rooms 1 and 4 but that room 5 experienced higher temperatures close to the heaters and lower temperatures further away.  The minor differences between rooms 1 and 4 are not considered to be significant, and thus it appears that the radiation in room 1 did not have any appreciable effect on heat transfer in the salt. The higher temperatures in room 5 were almost certainly associated with the poorer heat transfer characteristics of the about 25 to 30% shale and anhydrite interbedded with the salt over the 12-ft depth of the array holes. These measured temperatures were compared with the theoretical calculations in the preliminary design of the experiment. The theoretical calculation assumed an infinite salt medium; that is, the rooms also were filled with solid salt. The heat losses to the room air were considerably greater than if the salt had been solid, and the in-place heat dissipating properties of the salt also appear to have been somewhat better than the 100°C values assumed in the calculations. Therefore, it was necessary to raise the power per array hole from a nominal 1.5 kW to 2.1 kW to obtain a peak salt temperature of 200°C at the center of the arrays (Bradshaw and McClain, 1971).

## Brine Migration and Off-Gas Condensate

Bedded salt brine inclusions from the Lyons, KS area were evaluated for brine flow characteristics under elevated temperature, pressure, and radiation effects.

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PSV investigations (Bradshaw and Sanchez, 1969; Bradshaw and McClain, 1971) of 'negative crystals' (cavities) found that small quantities of brine trapped in these cavities migrate toward a heat source. The driving force for the migration is the difference in solubility between the warm and colder sides of the brine inclusion. Theoretical diffusion models indicate that the migration rate is a function of temperature and is directly proportional to the temperature gradient. Calculated migration rates for a 1°C/centimeter (cm) gradient ranged from about 0 at 20°C to 7.7 cm/yr at 300°C. The theoretical predictions were found to be in reasonable agreement with migration rates measured in the laboratory, although there was considerable spread in the experimental data.  Specimens consisted of relatively pure salt crystals from the Hutchinson mine, about 2 1/2 cm on a side, containing brine cavities between 2 and 10 mm in maximum dimension. Thirty-one rate measurements (on twelve separate cavities) were obtained, covering the temperature range of 75-244°C, with gradients ranging from 4 to 34°C/cm. Migration periods varied from about 20 to 358 hours, and the observed distances of migration ranged from 0.8 to 8 millimeters (mm). The theoretical predictions also tended to confirm the approximate (but difficult to measure) rates of brine migration into a number of heated holes (salt wall temperatures up to 200°C).

Using the migration rates indicated by the theory, calculations were then done to determine what might be expected in an actual disposal facility. They were based on the relationships of temperature versus time and distance for a typical high-level future solidified-waste disposal facility. Assuming 0.5% by volume of water in the salt, a total inflow per waste container disposal hole of 2-10 liters (L), taking place over a period of 20-30 years after burial of the waste was expected. The peak inflow rate would occur at around 1 year after burial and in the range of 200 milliliters (ml) to 1 liter per year per hole. This range corresponds to about 0.5-3 ml/day/hole, which is similar to the range, estimated in the demonstration waste container holes. This water inflow rate would be expected to taper off and approach zero after 20-30 years

Boch et al., (1972) reported investigations for the transport of water vapor through crushed salt beds and indicated little or no alteration of the bed in instances where condensation does not occur, but significant modification of the gas transport characteristics of the bed, including plugging, in regions around and above areas of condensation.

Holdoway (1972; 1974) conducted and reported petrofabric examinations of salt samples from a region adjacent to array hole 2 in room 1. This region was located in a direction outward from the periphery of the array of waste canisters. Evidence for brine migration was observed, but only a few trails crossed crystal boundaries. There was some evidence that droplets were spreading on grain boundaries. These observational results appear to be in support of the postulation that brine was trapped on grain boundaries during the heating phases of the PSV experiment (Jenks 1979).

Three of the heated arrays were equipped with an off-gas condensate collection system that were designed to measure the rate at which moisture, and other parameters, were entering the array holes due to the migration of brine inclusions in the salt.

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Upon shutdown of the mechanical heaters, trapped moisture was released and captured in the system. The off-gas flow produced a slight drop in wall temperatures reversing the temperature gradient. Under normal conditions the inner wall of the hole has the highest temperature, after a few minutes of power outage the inner wall temperature was lower at some points in the salt. Jenks (1979) suggested that the brine was trapped on grain boundaries during heating and that the release of tangential stresses allowed the grain boundaries to open sufficiently for the brine to escape to the air gap space. There was also radiation hardening of the surface layer of salt, producing brittle salts that were more prone to rupture than the un-irradiated salt therefore releasing additional moisture to be captured by the system.

Bradshaw and McClain, (1971) estimated the minimum and maximum water inflows into the array holes was between about 0.4 and 3.0 ml/day per array hole for room 1 and 0.2 to 2.8 ml/day per hole for room 4. These rates are about what would be calculated from the theoretical migration rates.

The amount of water collected in the first two days after shutdown of all three arrays is about an order of magnitude greater than that collected during the entire prior period of operation. The final total collection was about 11 liters in room 1, and 12.5 liters in room 4.

Bradshaw and McClain, (1971) concluded that in an actual disposal operation, there would be no air in the borehole annulus and no air flow. Also, with the heat being supplied by radiation alone (no external heat source), the heat would slowly dissipate because of radioactive heat decay and a temperature gradient reversal would not occur.

Jenks (1979) expanded on the theoretical and experimental work of former researchers (cited in Jenks, 1979) on thermomigration of brine from Lyons and Hutchinson mines and correlated rates up to 250°C. He derived an empirical equation for $V/G_s$ (migration velocity of brine inclusion per unit temperature gradient of the salt), which represented the maximum values of thermal gradients.

Considerations of the effects of stressing crystals of bedded salt on the migration properties of brine inclusions within the crystals led to the conclusion that the most probable effects are a small fractional increase in the solubility of the salt within the liquid and a concomitant and equal fractional increase in the rate of the thermal gradient induced migration of the brine. The application of high pressure could reduce the value of the kinetic potential from that prevailing in the absence of the pressure, but this would not affect the maximum rates predicted by the Jenks equation.

The greatest uncertainty relative to the prediction of rates of migration of brine into a waste emplacement cavity in bedded salt is associated with questions concerning the effects of the grain boundaries (within the aggregates of single crystals which comprise a bedded salt deposit) on brine migration through the deposit. It is likely that the grain boundary trapping will tend to retard brine migration under the conditions expected to prevail with probable repository

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designs ($G_s$ < 2°C/cm maximum, impurities present on grain boundaries, and boundaries compressed by thermal expansion of the salt) (Jenks, 1979).

The results of some of the estimates of rates and total amounts of brine inflow to HLW waste packages emplaced in bedded salt were included to illustrate the inflow volumes which might occur in a repository. These estimates, which are based on the results of temperature calculations reported by others, employed the assumptions that (1) the salt contained 0.5 volume percent brine inclusions, (2) these inclusions migrated at the maximum rates shown by the Jenks equation, and (3) grain boundaries had no effect on the migration. The results of the brine inflow estimates for 10-year-old HLW emplaced at 150 kW/acre indicated inflow rates starting at 0.7 liter/year and totaling 12 liters at 30 years after emplacement. (Temperature calculations did not extend beyond *35* years).

The results of the estimates for 10-year-old pressurized water reactor emplaced waste at 60 kW/acre indicated a constant inflow of 0.035 liter/year for the first 35 years after emplacement (Jenks, 1979).

Results obtained from PSV suggested that stored radiation energy had little, if any, influence on the rate of brine flow into the emplacement cavities in the salt. No direct information regarding the effect of stored energy on the solubility of salt is available; therefore Jenks (1979) recommended that experiments be undertaken to provide such information.

**Trapped Moisture Effects**

To determine the effect of temperature on salt, 1- to 2-lb samples were heated to temperatures up to 400°C from the Hutchinson mine. Bradshaw and McClain (1971) found that the salt exploded when heated to ~280°C. Therefore the authors performed quantitative measurements of the amount of water released with more detailed observations of the effect of temperature on the Hutchinson and Lyons salts carried out in a "bomb." When the salt was heated, there was initially a large disintegration at a temperature above 250°C, followed by lesser events at random temperature increases up to the upper limit of heating.

There was a significant difference in the moisture content between the samples from the Hutchinson (0.4%) and Lyons mines (0.2%). The variation in the water content is apparently due to the random distribution and size of these inclusions throughout the salt.

Several mechanisms for the fracturing upon heating were postulated. The salt from a given site "exploded" at nearly the same temperature regardless of the rate of heating. These considerations, along with the observed release of steam, led to the conclusion that the greatest single cause of the disintegration process was the pressure of the heated brine.

Bradshaw and McClain (1971) analyzed and tabulated shattering (fracturing) temperatures for salt samples taken from various locations (bedded and domal). They found that bedded salt from all but one of the locations shattered at temperatures between 250 and 380°C, while none of the dome salts were affected at temperatures up to 400°C (No negative crystals could be found in the

dome salt samples.) A few samples of Hutchinson salt which were irradiated to exposure doses of $5 \times 10^8$ rads or greater fractured between 260 and 320°C. Bradshaw and McClain (1971) concluded that radiation will have little effect on fracturing temperatures.

## Isotope Migration

Boch et al., (1972) reported on a series of experiments conducted on crushed salt backfill that was subjected to fission and actinide radiation exposure. In initial experiments, waste containing Cs-137, Ru-106, or plutonium was placed at about the midplane of a column of crushed salt. The transport of isotopes up or down a given column was monitored by scanning each column at about 1-month intervals. The columns containing Cs-137 and Ru-106 were held at 340°C while the column containing plutonium was maintained at ambient temperatures. The results showed that, after about 6 months of exposure, no transport of cesium, ruthenium, or plutonium had occurred.

## Radiation Effects

Boch et al., (1972) reported experimental and theoretical information on radiation damage and energy storage in oxides and silicates. They concluded that any energy storage in typical calcined waste oxides and glassy solids would result predominantly from displacements or "spikes" caused by elastic collisions of the heavy recoiling nuclei that are formed in the alpha-disintegration of the transuranic elements within the wastes.

Thermal energy storage in the radioactive wastes is likely to be <200 cal/g, but the possibility that it will be higher in some systems cannot be excluded. Temperatures greater than 1000°C may be needed to affect the release of all stored thermal energy from some wastes. The release will not be spontaneous unless there is a stepwise increase in temperature to a high level at which rapid release is initiated. Radiation damage in radioactive wastes can be investigated experimentally with synthetic wastes, using fast-neutron irradiation under conditions that can be achieved in a research reactor.

Boch et al., (1972) initiated a program of experimental studies aimed at establishing the amounts of stored energy in rock salt under repository conditions (maximum gamma-ray doses and intensities of $\sim 2 \times 10^{11}$ rads and $\sim 5 \times 10^5$ rads/hr at temperatures ranging up to 330°C. Using a drop calorimeter at 500°C, they determined the stored energy in samples of synthetic crystals of NaCl which had been gamma-irradiated to $1.5 \times 10^{10}$ rads at $10^7$ rads/hr and at 95°C. Their average value of 14.6 cal/g exceeded, by factors of 1.7 to 2, to those reported by other investigators who used heat-of-solution calorimeters. These evaluations were higher than the values, approximately 1 cal/g, previously reported for synthetic salt crystals that had been irradiated at ≤80°C to comparable doses, but at higher dose rates (>$10^9$ rads/hr), with van de Graaff electrons. The explanation for the latter discrepancy remains to be established. The difference between the results of the two calorimetric methods can be reasonably explained by assuming that aqueous dissolution of radiation defects in NaCl results in the formation of certain species in addition to $Na^+$ and $Cl^-$. The heat of formation of these is less

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than that of $Na^+$ plus $Cl^-$ so that some of the energy associated with the defects is not measured in a heat-of-solution measurement.

It was conceivable that a dose-rate effect exists, in which migration and clustering of defects into relatively stable aggregates (colloids) become important at the longer exposure times prevailing at the lower dose rates. The possible products of the dissolution of the radiation defects which are consistent with available information include $H_2$, $ClO_3^-$, and $H_2O_2$ (Boch et al., 1972).

Boch et al., (1972) conducted several experiments as specified in Bradshaw et al., (1964) on Lyons salt to obtain estimates of the pressure of gas within the gas-phase bubble. They concluded that the gas pressure within a cavity is 1 atm or less. Also, they concluded that the maximum concentration of air within the brine will be about 0.002 molar (M), and accordingly, that the effects of this air on radiolysis will be negligible relative to the concentrations of radiolytic products (>0.01 M at the least).

**Thermal Analyses**

Parametric studies of the high-level facility were conducted for a 1000-ft depth and the stratigraphy at the Lyons site, with room and pillar width, waste container array and spacing, and waste age and composition as variables. Preceding this effort, temperature dependent thermal conductivity was included in the three-dimensional conduction code, and criteria associated with limiting temperatures were modified to achieve greater consistency. Room widths of 15 to 50 ft and corresponding pillar widths of 25 to 50 ft were considered. The results of the analysis indicated a preference for the 18-ft room, 30-ft pillar combination because of a significantly higher maximum permissible net loading surface density. The corresponding gross loading surface density for 10-year-old waste is about 6 metric tons of waste nuclides per acre (158 kW/acre). The permissible power per waste package was dependent on the age and thermal properties of the waste, the diameter of the container, the time dependence of the backfill thermal properties, and handling considerations. A reasonable upper limit appeared to be 5 kW/waste package for 10 year-old waste. Numerous other miscellaneous calculations were made, all of which tend to substantiate the technical feasibility of the high-level waste repository (Boch et al., 1972).

The last experiment of Boch et al. (1972) entailed the adjustment of the temperature profile of the crushed salt bed with time. Although the effects of factors that control the temperature gradients are open to question, a set of time temperature data (cited in text) was prepared for the thermal analyses. These data were applicable in an approximate manner to a single 5-kW waste container (6 in OD x 10 ft) buried in a 10-in-ID by 18-ft deep borehole. At time zero, adjacent containers (15 ft away) and borehole backfill was assumed to be present.

Salt in the high-temperature regions (~400°C), which simulated the top of the waste container, were not altered appreciably; it either remained dry or was moist only for a brief period of time. Metal components in this region indicated no corrosion effects; thus it was clear that high-power-density containers had some merit because brine cannot exist in these regions at atmospheric pressure, and

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the absence of brine mitigates metal corrosion.  It was not clear whether moisture-induced consolidation in the crushed salt backfill would produce a plug that would sustain high gas pressures. The results suggested that the formation of a plug cannot occur during early time spans.  However, effects of borehole closure caused by plastic flow of the bedded salt were not considered; in addition, the water vapor source concentrations may not be realistic.

Boch et al. (1972) completed measurements of the thermal conductivity, $\lambda$, identified in Bradshaw et al. (1964), of both "fine" and "medium" salt powders in a radial heat flow apparatus. The results showed that $\lambda$ is sensitive to the gas phase and to imposed stresses. An instrumented probe was employed in a salt block to simulate the short-time behavior of a waste can in the repository as the hole was backfilled. From a reference temperature of 500°C in air, the waste container would experience a temperature rise to about 560°C in an empty hole, decreasing to about 260°C after the salt powder is added. If a molten salt eutectic mixture was poured around the container, the container experienced a momentary rise to about 560°C and then a rapid decrease to about 210°C.

### Simulated Waste Container Test (SWCT)

The objective of this test was to obtain additional data on the effect of moisture on stainless steel and carbon steel containers in the relatively pure salt in the floor of the experimental area and in the interbedded salt and shale in the original mine floor. Examination of the modified pillar heaters and of the SWCT heaters revealed gross cracking both in the 304L stainless steel pillar heater (in pure salt) and in one of the 304L SWCT heaters. Also, 304L pipes in the modified heater tests were severely corroded. The severe cracking and severe corrosion were in parts of the heaters that were cooler and on which water condensed. Metallographic examination of the 304L stainless steel modified pillar heater revealed the cracking to be caused by stress corrosion.

Metallographic examination of the carbon steel modified pillar heater showed a corroded outer surface but no evidence of penetration was observed. There was apparently little, if any, loss of wall thickness to corrosion (Bradshaw and McClain, 1971).

## 3.1.2 SUMMARY AND APPLICABILITY OF THE PSV DISPOSAL CONCEPT

The proposed disposal concept for PSV included both HLW and alpha waste facilities on the surface and the underground in bedded salt (Figure 3-3). Alpha waste containers (drums, boxes) were to be stacked in disposal rooms and backfilled with crushed salt.  The HLW canisters were to be placed in boreholes in the floor of the mine rooms and backfilled with crushed salt.

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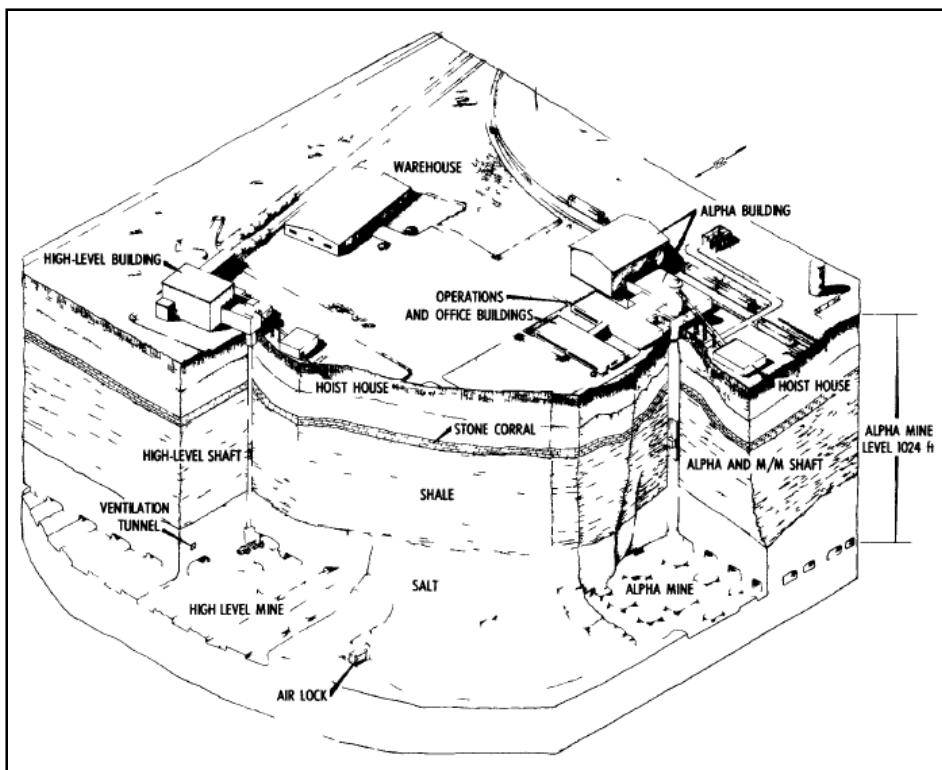
**Figure 3-3:  Cross Section of the PSV Disposal Concept (from Blomeke, 1977)**

The primary tests conducted in the PSV experiments simulated heat transfer into a mine pillar and two rooms in the floor of the mine. The heating effect did not significantly affect the salt pillar or floor of the mine. Therefore, notwithstanding the additional information about the thermal and mechanical behavior of salt, any insight from heater-test insight is applicable to borehole waste emplacements.

### 3.1.3  RELATIONSHIP TO UNDERGROUND TEST PROGRAMS

Salt thermal response investigations performed for PSV with actual and simulated heat sources are directly applicable to disposal of heat generating radioactive waste.  The salt was heated to 200°C for almost two years (693 days) where brine migration/condensation, salt decrepitation, isotope migration, radiation, and container corrosion were evaluated.  The lessons learned, test techniques and methods developed and applied, and data accumulated are still applicable to any underground test program in salt and remain beneficial to test programs in other geologic media as well.

Recommended areas for test improvement from the PSV field tests based on the literature review in Section 3.1.2 include:

- Investigate brine flow migration that demonstrate the effect of salt grain boundaries under repository conditions
- Investigate the effects of borehole closure of the crushed salt to observe the behavior of water vapor transport

- Investigate at higher temperatures (>250 °C) salt decrepitation over a range of brine cavity sizes
- Investigate whether moisture-induced consolidation in crushed salt backfill will produce a plug that will sustain high gas pressures. PSV results suggest that the formation of a plug cannot occur during early time spans

Some of these areas of investigation have been addressed in the Avery Island and Asse salt mine discussions in the subsequent sections.

## 3.2   AVERY ISLAND: DOMAL SALT

In 1974, the radioactive waste isolation program, which had been limited to bedded salt formations, was significantly broadened to include investigation of other rock types and other types of salt deposits. Part of this expanded investigation program focused on the Gulf Coast salt domes, especially those of the interior basins. By 1977 fundamental questions relating to the hydrologic and tectonic stability of salt domes had been satisfactorily resolved (Martinez et al., 1976; 1977), and the salt domes of the Gulf Coast interior basins were deemed viable alternatives to bedded salt for the location of potential repositories. With the initiation of exploration and site investigation programs directed at salt domes, it was recognized that the in situ performance database was entirely a product of previous testing in bedded salt. However, salt domes represented a different geologic and geometric configuration. Within the domes, the salt is in a deformed state because of its diapiric ascent and emplacement. Thus, confirming of the validity of the previously developed in situ performance database was deemed necessary. Potential domal salt sites were investigated and arrangements were made with International Salt Company to perform a testing program on the 500-foot level of their existing and operating Avery Island domal salt mine in southwestern Louisiana.

Avery Island salt- dome-like-structre is located in Iberia Parish, Louisiana. The dome is about 3 miles  inland from Vermilion Bay, which in turn opens into the Gulf of Mexico.  The dome is a large salt mass measuring about 3 miles long and 2 1/2 miles wide.  The salt dome was created by the upwelling of ancient evaporite (salt) deposits that exist beneath the Mississippi River Delta region. At its highest point, Avery Island is about 163 feet above mean sea level (Kupfer, 1983). It covers about 2,200 acres and is about 2.5 miles across at its widest point.  A variety of salt industries associated with the dome appeared during the periods of the 1812 and Civil Wars when salt was recovered through wells and quarries.  The first shaft (8 ft x 8 ft) was sunk in 1867 to a depth of 83 feet.  A number of mining operations operated by different companies followed but were fraught with inflows and sinkholes.  With the knowledge of the historical water problems, the Avery Rock Salt Mining Company sunk a new shaft to a depth of 518 feet in 1898.  The shaft was completed in 1899 and is still in use today.  A ventilation shaft was sunk in 1922.  Mining has continued at various levels over the years and is still active today.  Additional historical information on Avery Island may be found in Vaughan (1925) and Kupfer (1983). Figure 3-4 provides a map of the entire 500-level and its shaft locations (the Steam and Air Shafts bottom out on the 500-level, but the Production (shown as "New") Shaft extends down to the 1300-level. Figure 3-5 shows the positioning of the three heater tests within the test area (labeled as former test area in Figure 3-4).
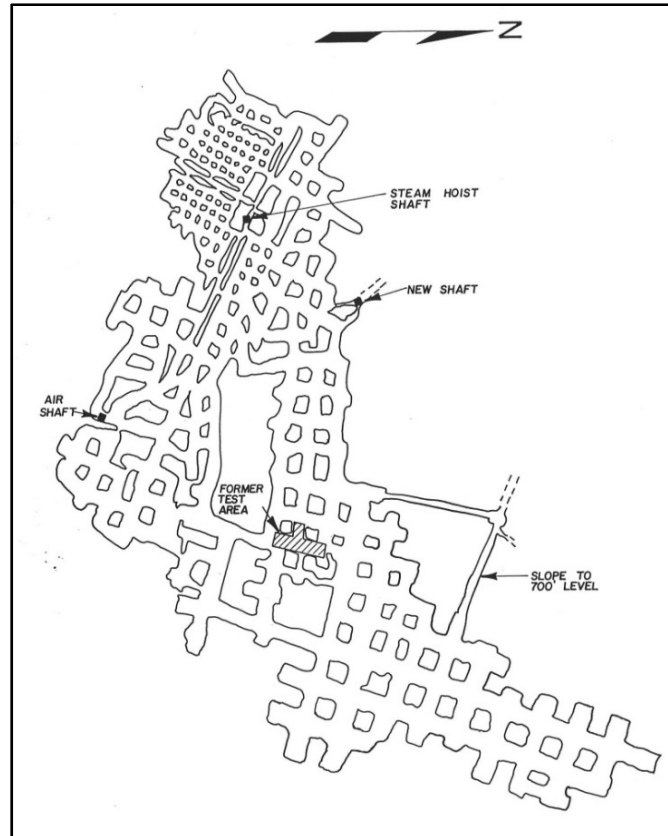
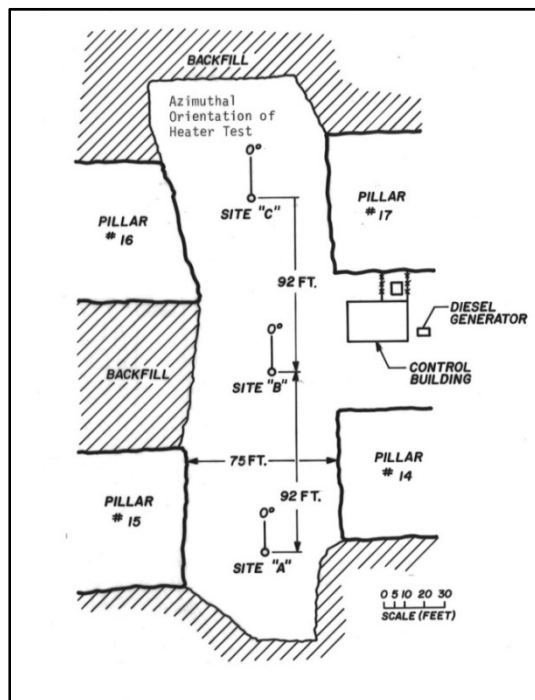**Figure 3-4: Avery Island Mine 500-Level Showing Shafts and Heater Test Area**



**Figure 3-5: Heater, Corejacking, Permeability, Brine Migration, & SNL Cooperative Studies Test Areas**

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### 3.2.1   SUMMARY OF INVESTIGATIONS

The purpose of the Avery Island testing program was to perform a limited number of heater tests designed either to confirm that the behavior of dome salt is similar to bedded salt or to demonstrate that the differences are great enough to make the existing bedded salt database inappropriate for dome salt applications. The original intent of the Avery Island testing program was not to repeat the full scope of the testing performed in PSV investigations, which had been completed nearly 10 years earlier. However, it was expected that the availability of an underground test facility available in salt would lead to further suggestions and proposals for additional test programs. Consequently, a secondary purpose of the Avery Island testing program was to provide a salt test facility where other experiments in support of the overall nuclear waste program could be performed.

Over a 5-year period, a comprehensive field testing program was conducted in the Avery Island salt mine. The major elements of the program were three heater tests (A, B, and C), a brine migration study, permeability measurements, a series of axisymmetric corejacking tests, and a series of instrumentation development activities performed jointly with SNL. The time line for the associated in situ test activities is given in Table 3-1.

| Date | Event |
|---|---|
| **March 1976** | DOE authorization and initial negotiations with International Salt Company for lease of underground space |
| **July 1977** | Heater test designs finalized |
| **January, 1978** | Installation of heater tests started |
| **June 1978** | Heater tests initiated |
| **July 1979** | Brine migration tests installed |
| **May 1980** | Corejack testing started; permeability measurements performed |
| **March 1979 – June 1981** | Sandia cooperative studies performed |
| **July 1981** | Sites A and B heater tests terminated |
| **July 1983** | Site C heater test terminated |

**Table 3-1:  Time Line of Avery Island In Situ Test Activities**

**Heater Tests**

The Avery Island heater tests had three technical objectives:

1. Establish the in situ thermal properties (thermal conductivity and heat capacity) of dome salt at the temperatures of interest for a waste repository for comparing bedded salt and laboratory-derived data. A subsidiary part of this task was the validating of the methods used to calculate temperature distributions around heat sources.
2. Determine the mechanical response of dome salt when heated by isolated heat sources and provide information on the closure of open heater borehole closure.
3. Establish the exposure conditions and corrosion characteristics of waste packages. These conditions include the amounts of brine and certain gases that enter and are trapped in the backfill or borehole annulus during the heating period and the borehole wall degradation.

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To meet the above technical objectives, 3 separate and thermally isolated heater tests referred to as Sites A, B, and C were installed in the mine floor on the uppermost level (167 m below mean sea level) of the Avery Island Mine. The initial design of the heater tests was performed by Oak Ridge National Laboratories (Fairchild and Jenks, 1978). Table 3-2 lists the characteristics and attributes of the heater sites. Figure 3-5 shows a cross-sectional schematic of the three heater test configurations.

| Characteristics | Site A | Site B | Site C |
|---|---|---|---|
| Heater Power Level | 6 kW | 3 kW | 4 kW |
| Number of Peripheral Heaters/Power Level | None | None | 8/0-700 Watts |
| Sleeve Diameter/Schedule Number | 0.305 m (12 inch) Schedule 80 | 0.305 m (12 inch) Standard Weight | 0.305 m (12 inch) Standard Weight |
| Backfill Type | None (air) | None (air) | Crushed salt |
| Borehole Annulus Enclosure | Rock wool | Butyl rubber | Crushed salt |
| Number of Thermocouples (T/C) on Heater | 3 | 3 | 3 |
| Number of T/C on Sleeve | 14 | 3 | 4 |
| Number of T/C on Borehole Wall | 0 | 0 | 5 |
| Number of T/C in Salt | 112 | 32 | 32 |
| Maximum Radial Distance to T/C in Salt (m) From Heater Centerline | 3.38 | 0.97 | 0.92 |
| Minimum Radial Distance to T/C in Salt (m) From Heater Centerline | 0.30 | 0.30 | 0.27 |
| Maximum T/C Depth (m) From Floor | 8.36 | 6.84 | 7.00 |
| **Heater Assembly Dimensions (m)** | | | |
| Heater Outside Radius | 0.079 | 0.109 | 0.109 |
| Sleeve Inside Radius | 0.145 | 0.152 | 0.152 |
| Sleeve Outside Radius | 0.162 | 0.162 | 0.162 |
| Borehole Radius | 0.22 | 0.20 | 0.20 |

**Table 3-2: Characteristics and Attributes of Heater Tests**
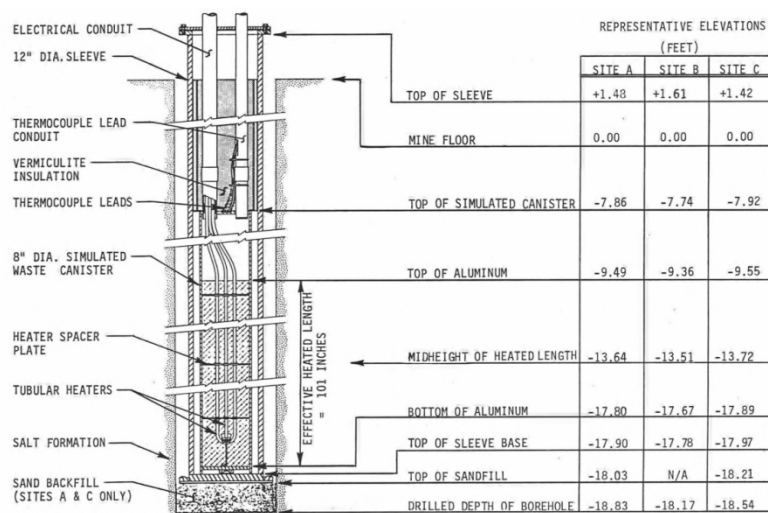


**Figure 3-6: Heater Test Schematic (from Van Sambeek et al., 1983)**

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A compilation of the measurement results for the three heater tests is given by Van Sambeek et al., (1983). This report presents data spanning from test start-up through 1,000 days of heating. The report includes data from temperature measurements, heat flux measurements, and deformation measurements (floor heave, differential floor expansion, borehole closure, and stress change).

The heater tests had heating periods of about 1,000 days, which was considered long enough to achieve steady-state temperatures in the ventilated room. The temperature measurements made in salt were smooth with respect to time with a high degree of radial consistency. The displacement instruments performed reliably with no obvious inconsistencies in the displacement data.

A sample of approximate temperatures measured near the heater midheights is given in Table 3-3; the preheating salt temperature was about 26°C. Figure 3-7 illustrates the temperature distributions for each of the tests.

| Location | Site A (6 kW) | Site B (3 kW) | Site C (4 to 9.6 kW) |
|---|---|---|---|
| Heater surface | 384 | 289 | 314 |
| Outside Sleeve | 280 | 160 | 196 |
| Crushed Salt | n/a | n/a | 160 |
| 1-ft into salt | 158 | 81 | 158 |
| 3.2-ft into salt | 84 | 51 | 110 |
| 4.9-ft into salt | 64 | n/a | n/a |
| 10.7-ft into salt | 41 | n/a | n/a |

**Table 3-3:  Approximate Temperatures (°C) Measured at Heater Midheights**



**Figure 3-7:  Temperature Distributions After 1,000 Days of Heating for the 3 Heater Tests**
**(from Van Sambeek, 1982)**

In general, the agreement between measured and later calculated temperatures (Figure 3-8) was good at all radii in the salt between the top and bottom of the

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heaters. The measured temperature rise was systematically as much as 30% greater than that calculated between the top of the heater and the floor – the annulus betwe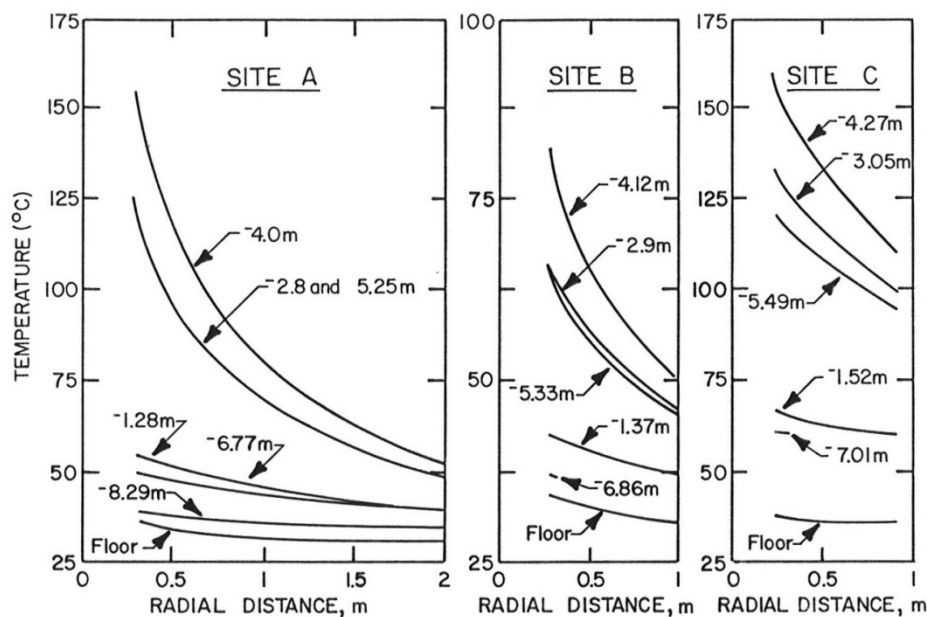en the sleeve and salt had become salt encrusted above the heater which promoted heat conduction or the calculation apparently transferred too much heat from the floor by convective cooling and radiation transfer to the roof. The best agreement between calculated and measured temperatures was obtained when the laboratory-measured thermal conductivity for the salt was increased by 20%.
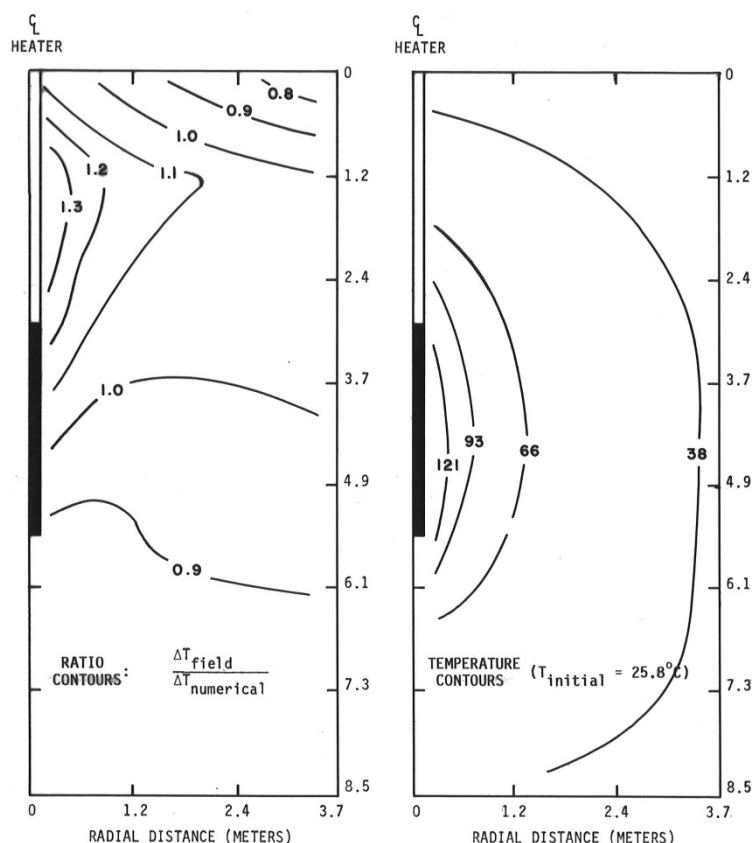


**Figure 3-8: Post-Test Calculations of Temperature Distributions for Site A after 1,000 Days of Heating (after Wagner, 1985). [Right figure shows temperature contours; left figure shows the ratio between field-measured and numerical-model calculated temperatures.]**

Two types of displacement were measured: (1) floor heave and differential expansion around the heater tests and (2) roof-to-floor closure and pillar expansion around the test site. Floor heave is the concentric uplift of the floor around the heater borehole as a consequence primarily of thermal expansion and secondarily in response to salt creep. The approximate amounts of floor heave were 1, 0.5, and 2 cm for Sites A, B, and C, respectively. The majority of the floor heave occurred within the first 100 days after the heaters were set to full power. The later calculated floor heave was greater than the measured floor heave, which suggested that the calculated thermoelastic stresses were too great. The differential expansion was measured using multiple-point borehole extensometers in vertical boreholes. The measured floor movements relative to the deepest anchor (11 m) were: 1.1 to 1.3, 0.6 to 0.8, and 1.5 to 1.9 cm for Sites

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A, B, and C, respectively. These displacements agree with the less precise floor heave amounts.

The average roof-to-floor closure rate (expressed as a strain rate) was $5.3 \times 10^{-6}$ per day. The pillar expansion rate (expressed as a strain rate) was $1.6 \times 10^{-6}$ per day between the rib and the pillar center at a vertical location about 3 m above the floor in the 7.5 m tall pillars.

The heat-flux meters attached to the floor near the Site A heater test suggested a convective film coefficient (Newton's law of cooling) between 6.8 to 9.1 W/hr per $m^2$ per °C difference between the mine ventilation temperature and the floor temperature. Data from the heat-flux measurements are shown in Figure 3-9.
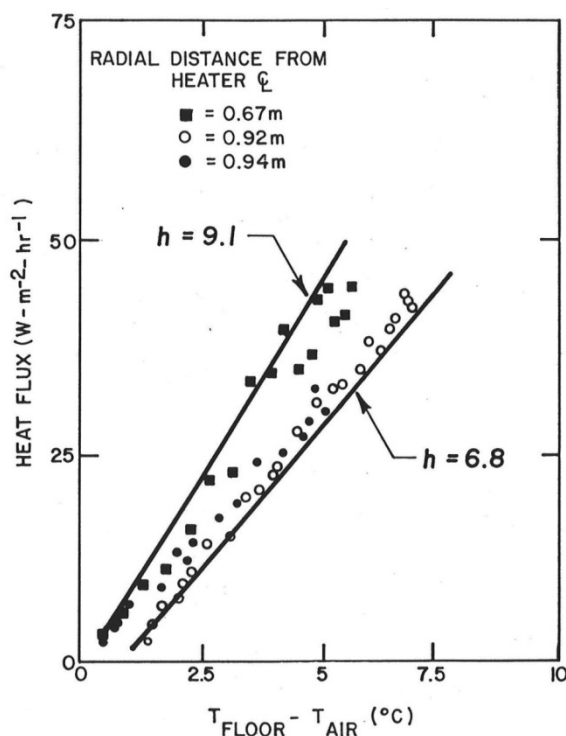


**Figure 3-9: Measured Heat Flux From the Floor at Site A as the Floor Temperature Increased Above the Ventilation Air Temperature (from Van Sambeek et al., 1983)**

**Brine Migration Study**

The in situ brine migration study objects were to: (1) examine the migration of synthetic and natural brines in salt in a temperature field produced by electrical heaters and (2) develop requisite and more precise measurement techniques and procedures to use in future brine migration experiments.

In a more general sense, these experiments were intended to provide data relevant to brine inclusion migration in the vicinity of emplaced radioactive waste canisters. Brine migration will have considerable impact on the design and emplacement of backfill materials and other protective measures for isolating waste canisters from natural brine in a geologic repository in salt.

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The designs for the brine migration study addressed the following measurements:

- The areal extent of liquid brine inclusion (both natural and artificial) movement for an induced thermal gradient.
- The rate of brine inflow to the heat source for an induced thermal gradient.
- The possible influence of thermally induced microfracturing in salt around the heat source.

A complete description of the tests was published by Krause (1983). Three brine migration tests were fielded:

1. Site AB – natural brine movement under ambient temperature conditions (essentially a salt-drying experiment)
2. Site NB – natural brine movement in heated salt (1 kW heater)
3. Site SB – synthetic tagged brine in a borehole within the heated salt (1 kW heater).

Each site had a central borehole (heater borehole) within a pattern of accessory boreholes containing thermocouples or tagged brine (Site SB). The central borehole was purged with dried nitrogen and the moisture carried by the exiting nitrogen was measured. The heated tests lasted 250 to 300 days, while the ambient temperature test lasted about 150 days. Site SB had a power failure that resulted in a rapid cool-down and while Site NB had a daily uniform power reduction over a 30-day period. The moisture collection for the three tests is provided in Figure 3-10.
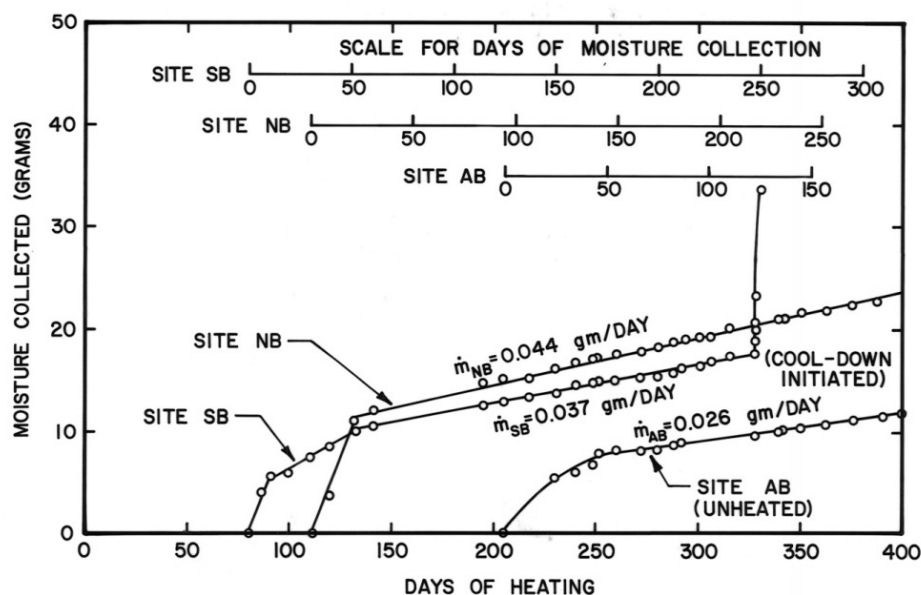


**Figure 3-10: Comparison of Moisture Collection From Three Brine Migration Tests (from Krause, 1983)**

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Comparing the pre- and post test measurements of permeability suggested that the cool down at Site SB caused a 4-order of magnitude increase in permeability. The accelerated moisture collection during the cool down process probably relates to the permeability increase. Posttest chemical and petrographic analysis of the salt obtained by over coring the tests did not reveal any substantial information. Some evidence of tagged-brine movement toward the heater borehole was found, but the movement was probably from permeation rather than brine migration through crystals. The investigators did conclude that their test method using "artificial and large" brine inclusions was inappropriate to studying natural brine inclusion migration.

**Permeability Measurements**

The objective of the permeability measurements was to measure and examine the permeability of in situ salt at different temperatures. This objective was achieved by developing a mechanical borehole packer using two test methods to measure nitrogen flow into heated salt.

The field data analysis was performed by comparing analytical solutions for idealized flow (Blankenship and Stickney, 1983). The results indicate that permeability decreases as temperature increases. This trend is reasonable considering that an increase in temperature causes thermal expansion of the individual crystals: thus, the interconnected porosity of the salt mass becomes tightened or completely closed.

Two types of borehole measurements in heated salt were performed: (1) falling head where the pressure drop in the borehole was monitored after an initial pressurization and (2) constant pressure where the flow rate was monitored while maintaining pressure in the borehole. Interpreted permeabilities ranged from $10^{-18}$ to $10^{-21}$ m$^2$ with the permeability systematically varying inversely with temperature of the salt (Figure 3-11). Considering the measurements were shallow in the floor, which is subject to dilation after mining, the permeability magnitudes are low. In addition to confirming the relative impermeability of salt, the primary benefit of these tests was that better test equipment was built for use at the WIPP.
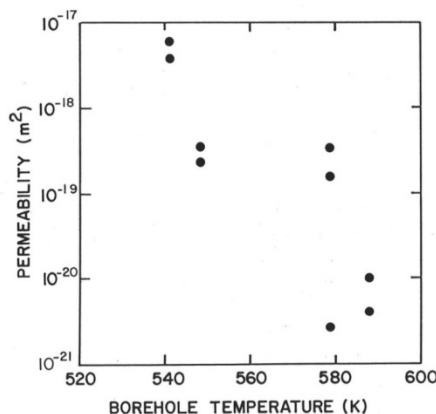


**Figure 3-11:  Interpreted Permeability from Borehole Measurements Made at Different Temperatures (from Blankenship and Stickney, 1983)**
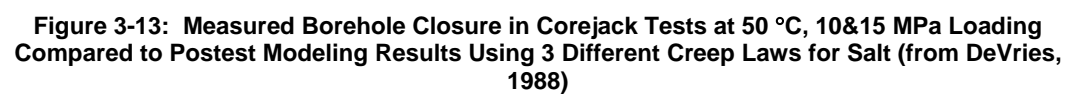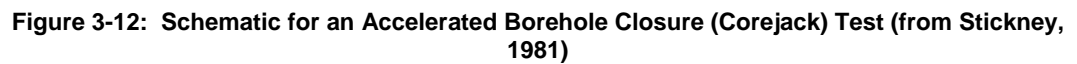
### Corejack Test Development

The objective of this series of experiments was to develop a field test with known and controlled boundary conditions in a geometry that could be easily modeled by numerical methods. One of the reasons for conducting field tests is to obtain data to validate numerical models. Although the Avery Island heater tests provided useful data for this purpose, the heater tests do not present an ideal situation from a modeling standpoint. The room geometry in the vicinity of the tests is complicated because the surrounding pillars are non uniform in shape, size, and spacing, and the roof height varies throughout the test area. Only an approximate two-dimensional approach can be used when modeling the heater tests. In addition, the initial state of stress in the surrounding salt is difficult to determine as in most underground settings.

The corejack test was designed in axisymmetric geometry with controlled boundary conditions representative of an expected repository environment (Van Sambeek, 1981). The corejack test consisted of applying constant pressure to the outside circumference of a large hollow cylinder of salt and monitoring the time-dependent closure of the cylinder's inside diameter. Provisions were made to heat the salt cylinder with electrical heaters so that tests can be conducted at elevated temperature. A schematic of the test configuration is illustrated in Figure 3-12. The test could also be used for site characterization in that it provided bulk thermomechanical response data.

The corejack test development was completed in three phases of testing at Avery Island (Stickney and Van Sambeek, 1981; Brekken et al., 1983; Van Sambeek and Stickney, 1984; Stickney, 1984). The first phase of testing was performed during 1980. This phase comprised one test at ambient mine conditions and two tests at elevated pressure (one of which was conducted at an elevated temperature of 60°C). Four tests were included in the second phase of testing conducted during 1981: two tests at ambient temperature and two tests at 60°C. At each test temperature, tests were conducted at corejack pressures of 10.6 MPa and 14.8 MPa. The third phase conducted during 1983 included a series of six tests, and all tests were at an elevated temperature. Corejack pressures were 10 MPa and 15 MPa conducted at 40°C, 50°C, and 60°C.

Post test structural analyses of the corejack tests were made using three constitutive models (DeVries, 1988). An example of the analysis of two heated corejack tests is shown in Figure 3-11 where measured borehole closure is compared to closures calculated using the three different constitutive models. The conclusion from the corejacking tests was that, of the three constitutive models, one model was inappropriate, one was better in the transient phase, and the other was best at predicting long-term (i.e., end of test) closure rates. A complementary conclusion was that the test method indeed produces a rigorous and well-controlled situation for collecting data that can be used to validate salt-constitutive models and numerical modeling techniques (still an axisymmetric configuration); however, the test method alone cannot directly define the appropriate constitutive model.

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**Figure 3-12:  Schematic for an Accelerated Borehole Closure (Corejack) Test (from Stickney, 1981)**



**Figure 3-13:  Measured Borehole Closure in Corejack Tests at 50 °C, 10&15 MPa Loading Compared to Postest Modeling Results Using 3 Different Creep Laws for Salt (from DeVries, 1988)**

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### Cooperative Studies

In a cooperative effort with SNL, several test development activities were conducted at the Avery Island test facility. These activities were in support of the WIPP Program. The main focus of these efforts was to develop field testing techniques in salt that were applicable to both the WIPP and the Office of Nuclear Waste Isolation (ONWI) Exploratory Shaft Programs. The major elements of the cooperative studies were a quartz lamp heater test, radar scanning experiments, a borehole closure experiment, stressmeter evaluation tests, and thermal conductivity probe measurements.

### Quartz Lamp Heater

The quartz lamp heater test objectives were to evaluate the performance of a new heater design using quartz lamps as a heat source and to evaluate the performance of a system designed to measure the amount of moisture released in a heater borehole (Ewing, 1981; Shefelbine, 1982).

### Radar Scanning

The efficacy of radar scanning to identify inclusions, structural discontinuities, and other anomalies within intact salt before excavation was examined. Radar scanning would provide an additional measure of operational safety during repository construction by locating such anomalies in the local emplacement area. During the operational phase of a repository, radar scanning could be used to locate an emplaced waste container in salt. The first series of experiments was conducted during November 1979 (Cook, 1980) and a second series of experiments was performed in June 1981 (Cook, 1982). The impulse radar system was used to scan a variety of objects at Avery Island with good success except in the presence of moisture on the mine floor. Thus, the tool was believed to be useful for scanning in salt formations before repository construction and for relocating emplaced materials during the repository operational phase.

### Borehole Closure

A pillar borehole test was conducted to assess the performance of a prototype borehole closure measurement tool. SNL developed the tool to measure closures in 200-mm-diameter boreholes. The tool consisted of an externally conditioned, rotatable LVDT (electronic displacement transformer) that was mounted on an assembly that centers the tool in the borehole. An electronic tiltmeter was used to establish the orientation in the borehole. The LVDT was rotatable through a 360° arc. Extension rods were used to position and rotate the tool at selected depths in a horizontal borehole. The demonstration was conducted in a horizontal 200-mm-diameter borehole drilled into a pillar 1.5 m above the mine floor (Stickney, 1987).

### Stressmeter Evaluation

Determining the in situ stress state at a repository location is essential for design and predictive calculations. Thus, a reliable stress measurement device used in salt was a major program requirement. Therefore, an evaluation of stress meters

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was performed by comparing three stress measurement devices: (1) IRAD™ vibrating wire stressmeter, (2) IRAD™ stressmeter with SNL-modified platens, and (3) a SNL-developed strain gage stressmeter. An earlier investigation of the standard IRAD™ vibrating wire stressmeter (Cook and Ames, 1979) that showed it is difficult to set the gage at the recommended preload because the platens tended to embed themselves in the salt. The gage response becomes erratic and not repeatable. These results led SNL to develop a modified platen design to use with the IRAD™ gage. A strain-gaged stressmeter, which also used these modified platens, was also developed. To compare the gages, each of the three types of gages were installed at multiple times at Avery Island near the ongoing Site B and Site C heater experiments in August of 1979.

The modified platen design was a definite improvement to the IRAD™ gage. The data from the gages using these platens were less erratic than that from the standard gage. In terms of absolute stress measurement near the heater tests, the results were inconclusive because none of the gages around the heater tests recorded significant stress changes. The output of the strain gage stress meters was very stable with the exception of those that failed in the brine-filled borehole. The modified IRAD™ gage aligned vertically in the pillar borehole gradually increased in reading during the monitoring period and reached a final value of about 5.5 Mpa. This was a reasonable reading for the 167-m depth of the test site.

**Thermal Conductivity Probe**

Thermal conductivity probe measurements were conducted to evaluate the performance of a SNL-designed line source thermal conductivity probe and to acquire in situ thermal conductivity data for Avery Island salt (McVey, 1981). The thermal conductivity probe consisted of a hollow cylinder that contained an encapsulated tubular resistance heater and six thermocouples. The dimensions of the probe were 25.4 mm in diameter and 0.94 m in length. Two of the thermocouples were located at mid-length of the heater, and two thermocouples were located near each end of the heater.

A total of 12 measurements were made in four separate boreholes at Avery Island during the fall and winter of 1980. One of the measurement boreholes was in heated salt near the Site B heater experiment (the temperature at this location was about 31°C). All of the boreholes were 25.9 mm in diameter and 1.8 m deep. A special drill bit was fabricated to drill these holes with 0.25 mm of clearance between the probe and the salt. The thermal conductivity values of Avery Island salt obtained using the probe were 5.8 W/m-K at about 26°C and 5.6 W/m-K at about 31°C (McVey, 1981). These values lie within the range of reported conductivities for Avery Island salt reported by others (Smith, 1976; Durham and Abey, 1981; Morgan, 1979).

## 3.2.2    SUMMARY AND APPLICABILITY OF DISPOSAL CONCEPT

The Avery Island test program fielded experiments and measurements related to waste disposal in canisters emplaced in vertical boreholes in the floor of rooms excavated in domal salt. The electrical-heater emplacements for the heater tests

were mockups of canisters and protective sleeves. The primary measurements were temperatures and displacements resulting from heating the salt-mine floor in three isolated locations. The heating effect did not significantly affect the salt pillars. Therefore, regardless of the additional information on the thermal and mechanical behavior of salt, any insight from heater-test data is applicable to vertical borehole waste emplacements.

The other tests and measurements at Avery Island provided more generic salt behavior observations and information (most often, test-method development) that are applicable to any disposal concept in salt. In particular, the brine-migration, permeability measurements, corejacking, stressmeter, and thermal conductivity probe were all first-of-their-kind measurements; hence, a learning curve was involved. The general tests concepts have application in other disposal applications.

The Avery Island testing programs and associated numerical-modeling exercises resulted in the following general conclusions:

1. The overall thermomechanical response of dome salt is similar to that determined for bedded salt in PSV.
2. Instrumentation is adequate for measuring temperatures and displacements in field tests in salt, but inadequate for measuring stress, particularly in heated salt.
3. Future brine-migration field tests might be useful for model validation, but fundamental theory and parameter definition must be derived from well-controlled laboratory testing.
4. Permeability of salt is low and hard to measure, and it appears to decrease with increasing temperature when the salt is reasonably confined so thermoelastic stresses develop.

An often overlooked aspect of the Avery Island heater tests is their decommissioning as a demonstration of "retrievability." The intact canisters were lifted from the sleeves followed by the sleeves being withdrawn from the boreholes. Even for the case of the salt-backfilled annulus (Site C) no extraordinary effort was required for the retrieval. All corrosion coupons were successfully retrieved from the Site B sleeve as evidence of the ease of removal.

### 3.2.3     RELATIONSHIP TO UNDERGROUND TEST PROGRAMS

The Avery Island test facility site was used for 5 years for measuring salt response and obtaining field data in support of needs related to radioactive waste isolation in salt.  The lessons learned, test techniques and methods developed and applied, and data accumulated are still applicable to any underground test program in salt, test programs in other geologic media benefit as well. Five major testing programs were conducted:

1. Three full-scale heater tests using simulated waste canisters.
2. A brine migration test series, including using synthetic brine.
3. Permeability measurements at ambient and higher salt temperatures.

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4. A development program that produced the corejack test procedure for measuring bench-scale salt response in an easily modeled configuration with controlled conditions of loading and temperature.
5. A cooperative effort with SNL that examined and tested instrument utility and further developed instruments and field test procedures.

From an observational perspective, none of the Avery Island tests caused the salt to be heated to greater than about 160°C, and only entailed a small volume of salt immediately surrounding the heater borehole. Thus, any concerns about salt decrepitation at high temperatures were not examined.

Experience from the Avery Island test facility identified technical areas requiring e additional work. A lack of agreement exists between measured and calculated responses for the heater tests and corejacking experiments. This lack of agreement might be attributed to the difference between the actual in situ properties of salt and laboratory-measured properties on specimens of salts, the salt constitutive models used to describe salt behavior, and the geometric approximations and simplifications and boundary-condition assumptions used in modeling.

Recommended areas for test improvement drawn from the Avery Island field tests include the following:

- Salt's thermal conductivity and linear thermal expansion should be measured in situ over a wider range of salt temperatures. The thermal conductivity affects the temperatures and temperature gradients, while the confined thermal expansion determines the thermoelastic stresses resulting from these temperature distributions.
- Laboratory measurement of properties under well-controlled homogeneous conditions needs to be performed and cannot be replaced by the corejacking test.
- The corejacking test does, however, provide significant value for numerical model validation using thermomechanical and creep properties for salt in an easily modeled geometry with well-controlled boundary conditions.
- The physical setting of field tests is important. The large room (about 30 m wide) used for heater test installation was initially believed to be sufficient to isolate the tests from the effects of the bordering pillars. However, the pillars did impact the results. Future test configurations should either replicate disposal-concept geometries and scale or be sufficiently isolated so that the mine structural elements (pillars, roof, floor, etc.) do not unduly influence the results.
- A need still exists for rock-stress measurement or stress "inference" instruments. Cells with encapsulated oil are too heat sensitive, and instruments that rely on an elastic response are ineffective because of salt creep. Hydraulic fracturing is typically incompatible with in situ stress experiments.
- If moisture measurements are necessary, the methods used at Avery Island were marginally suitable. Moreover, Avery Island salt is extremely

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dry (0.02 to 0.1 wt %) compared to bedded salts, which might have water contents greater than 1 weight percent.

## 3.3 ASSE MINE: DOMAL SALT

The Asse II salt mine, located near Wolfenbüttel, Germany, is a potash and salt mine that has been in operation for approximately 100 years. The history of the site and its use as a nuclear waste repository and research site is summarized at: http://www.endlager-asse.de/EN/2_WhatIs/_node.html, and therefore a brief summary is provided here. Since around 1900, the site has been the host of three salt mines, only one of which, the Asse II mine, is accessible today. Issues associated with water inundation in Asse I and III forced these mines to be abandoned. Active mining of rock salt in Asse II occured from 1909 to 1964, during which time about $3.8x10^6$ m$^3$ were mined.

In 1965, the Federal Ministry for Scientific Research and Technology initiated efforts to study the use of the Asse II for the possibility of using it as a radioactive waste repository. Following the identification of salt as a potential host rock for radioactive wastes by the National Academy of Sciences in 1957, a program was developed that included a series of in situ experiments to further the understanding of the response of salt when subjected to conditions similar to those expected in a nuclear waste repository. Storage of waste started on a trial basis in 1967, and soon thereafter ASSE II became the site for storage of most of the low- and intermediate-level waste for the Federal Republic of Germany. Some 125,787 drums of such waste were emplaced in 13 chambers in the southern and central flanks of the mine, at depths of 725-750 m. The waste storage operations were halted in 1978. Since then a series of decisions and law changes have led to the current status of the site. The Bundesamt fur Strahlenschutz (BfS) (the German Federal Office of Radiation Protection) plans to decommission the site by retrieving and relocating the waste and backfilling the current disposal area.
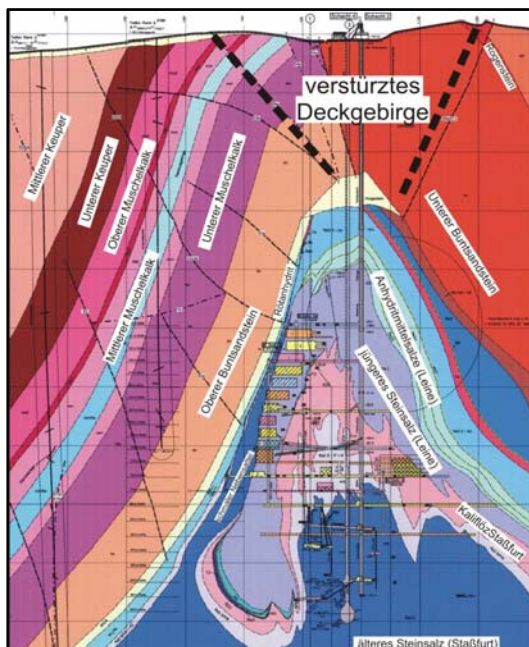


**Figure 3-14: Cross-Section of the Asse-Heeseberg Mountain Range Showing the Asse II Salt Mine, with Relationship of the Mining Area to the Salt and Overlying Geologic Units.**

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Figure 3-13 shows the salt-dome-like structure of the Asse-Heeseberg mountain range (Source: http://www.endlager-asse.de/EN/2_WhatIs/TheMine/_node.html). Because the Asse II mine was designed as a rock salt mine rather than a nuclear waste repository, chambers were mined to maximum salt extraction which in some areas, the mine is close proximity to the overlying and adjacent formations. The adjacent formations consist of mudstone, sandstone, and limestone layers. There are also numerous faults in the surrounding rocks in the southern flank (denoted by dashed lines).

As a consequence of the local geology, the large amount of salt removed, and the proximity of the mine to other permeable units, the mine has experienced significant brine inflow and mine stability issues. Large scale movement of the adjacent rock has led to a breaking up of the chambers, with "clefts" having developed through which groundwater can flow. Saline waters have flowed into the mine at depths between 500 and 575 m, and although this is not in the location where waste was emplaced, saline groundwater inflow and contact with the waste could not be ruled out unequivocally. Stabilization measures consisting of backfilling of the cavities with "salt grit" were implemented. Additional measures (injection of special concrete) were taken to fill the gap caused by slumping of the crushed salt after emplacement to reduce the time period between backfilling and the time when the backfill becomes a load-bearing body with no roof gap.

### 3.3.1    SUMMARY OF INVESTIGATIONS

In addition to being the site of low- and intermediate-level radioactive waste disposal operations, the Asse mine has served as the host for a series of field experiments examining the behavior of salt under conditions representative of a repository for HLW. A number of field campaigns were conducted, often with both German and international collaboration and funding to examine the evolution of intact salt, crushed salt, and the excavation disturbed zone (EDZ), also commonly referred to as the disturbed rock zone, or DRZ, for heat loads typical of potential disposal conditions of HLW. Figure 3-14, from Jockwer and Wieczorek (2008) shows the locations of the major in situ tests conducted at Asse, and Table 3-4 lists the tests and their primary purposes.



**Figure 3-15:  Map of the Asse Salt Mine and Locations of In Situ Tests Conducted**

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| Test Program | Purpose | Reference |
|---|---|---|
| **Brine Migration Tests 1983-1985** | Observe the effects of heat and gamma radiation on brine migration in salt | Coyle et al. (1987) |
| **TSDE – Thermal Simulation of Drift Emplacement 1990-1999** | Study the thermomechanical effects of direct disposal of spent fuel elements in a salt repository | Rothfuchs et al. (2003) |
| **DEBORA – Development of Seals for HLW Disposal Boreholes 1991-1999** | Investigations of crushed salt compaction in backfill and seals during borehole emplacement in salt | Rothfuchs et al. (2003) |
| **BAMBUS – Backfill and Material Behavior of Underground Salt Repositories** | Post-TSDE lab, field observation, and modeling studies of the temperature and stress dependent compaction behavior of crushed salt backfill | Bollingerfehr et al. (2004) |
| **ADDIGAS – Advective and Diffusive Gas Transport in Rock Salt Formations 2004-2007** | Examine issues of the advective and diffusive gas transport in the EDZ not resolved in previous projects | Jockwer and Wieczorek (2008) |

**Table 3-4: In Situ Test Studies in the Asse Mine**

In the subsections below, the objectives and the main findings of each of these field campaigns are described.

**<u>Brine Migration Tests</u>**

This project was a joint effort conducted by the U.S. DOE and the Federal Republic of Germany to examine the impact of heat on salt. The objective of the brine migration tests was to observe the effects of heat and gamma radiation on brine migration in salt (Coyle, 1983; Coyle et al., 1987; Kalia, 1994). Related objectives included development of test methods, providing data for the validation of numerical models, observation of coupled geochemical processes such as gas generation, radiolysis, and corrosion, and to observe the thermal-mechanical effects as impacted by the brine migration processes. Previously, laboratory studies on fluid inclusion behavior in salt had been conducted by many investigators (e.g. Jenks and Claiborne, 1981; Carter and Hansen, 1983; Roedder, 1981), with observation of the migration of inclusions up the temperature gradient in response to dissolution on the up gradient side of the inclusion, liquid-phase transport of dissolved salt in the inclusion, and precipitation on the cooler side, this led to a net migration of the inclusion toward the higher temperature over time. However, more complex behaviors are expected to occur in real systems at scales of many grains, whereas most laboratory scale work is performed on single grains or a few grains. A field-scale test of this nature allows one to examine the behavior at scales relevant to waste disposal.

As described by Coyle et al. (1987), large-scale experiments were performed in the main salt of the Asse mine in 1983-1985 to investigate these phenomena. Under the assumption that the disposal concept would be the emplacement of waste in boreholes, the test design called for the installation of heaters within vertical boreholes drilled into the mine floor, with heating selected to mimic the conditions of the disposal of heat-generating waste in a series of boreholes. Four tests were conducted, each consisting of a central borehole containing a 3000 W heater and a system for water collection in the annular region between the

borehole wall and the workings internal to the borehole. The test design called for a maximum salt temperature at the wall of 210$^{\circ}$C, and a gradient of 3$^{\circ}$C/cm at the wall. Peripheral heaters were placed in a set of 8 guard holes around the main heater to simulate the thermal gradient conditions likely to be seen in a repository setting. Both pressurized and atmospheric pressure conditions were established in the different tests to examine the differences that resulted. Cobalt-60 sources were placed within two of the holes to study radiolysis effects. Standard temperature and deformation instrumentation was installed to monitor the behavior of the system. The four tests were spaced about 15 m apart in the same drift to minimize thermal interaction between the experiments.

The quantities of collected brine in the cold trap system in each of the heated boreholes was much less than predicted during test design. For example, 122 mL was collected after 838 days in one test site, and 135 mL was collected after 654 days at another test site (Coyle et al., 1987). This was attributed to the use of laboratory-determined permeability values in the pre-test predictions. The apparent field-scale values results are much lower than the brine migration rates than those predicted from the higher lab permeability values. In addition, the pressurized borehole resulted in a lower migration rate, a result that is consistent with vapor-phase water transport (at a lower pressure gradient when the borehole is pressurized) for at least some of the water arriving at the borehole. In contrast to the surprisingly low rates of water movement, the thermal and mechanical behaviors of the boreholes were closer to that predicted by the models.

Finally, with respect to geochemical effects: 1) gamma radiation was observed to have noticeable effects on the collected gases; and 2) some hydrogen was detected in both the non-radioactive and radioactive sites, presumably caused by either corrosion reactions between the brine and metal in the borehole or produced from the hydrocarbons present in the salt.

### Thermal Simulation of Drift Emplacement (TSDE) Tests

This project was a long-term salt heater test program lasting from 1990-1999. The primary goal was to study the thermomechanical effects of direct disposal of spent fuel elements in a salt repository. The TSDE tests have been discussed as the most important in situ experiment performed in Germany on radioactive waste disposal in salt, due to the importance given to the concept of direct disposal of waste versus reprocessing, starting in the 1990's (Rothfuchs et al. 2003b). The main objectives of the test were: 1) observe the thermal, mechanical, and hydrologic response of salt under repository-relevant conditions; 2) test the use of numerical models to predict the behavior of salt backfill compaction over long periods of time over which significant drift closure would occur; and 3) examine the corrosion behavior of materials in a repository environment. Note that the BAMBUS studies described later are naturally paired with the TSDE tests, but the former focus on post-test observations and modeling of the results. In this section the focus is on the key experimental observations from the heater tests themselves.

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Key to the design of the TSDE tests is the configuration of the heaters, installed so as to mimic the direct disposal of heat-generating spent nuclear fuel casks on the drift floor, with crushed salt emplaced on top of the heaters as would be done in a repository for shielding purposes. Thus, the TSDE tests are a primary demonstration of the in-drift disposal concept. The three 6400 W heaters were emplaced in each of two 70 m long (by 3.5 m high and 4.5 m wide) drifts on the 800 m level of the Asse mine (Figure 3-16), and crushed salt from the mining operation was emplaced as backfill after sieving to remove the fraction greater than 45 mm. Heating began in 1990 and was continued for more than 8 years while the thermal and mechanical behavior of the system was observed.

After several months, temperatures in the surrounding medium reached their maximum of about 210°C and slowly decreased thereafter, reaching 170°C by the end of the heating phase. This behavior, reproduced in modeling exercises in the BAMBUS project, is characteristic of a system in which compaction of the crushed salt due to drift closure leads to an increase in the thermal conductivity over time.
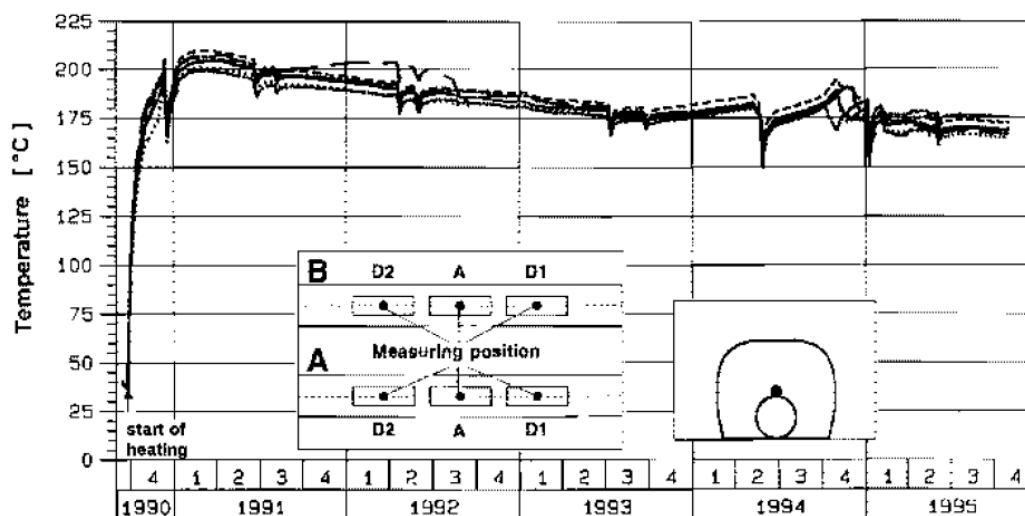


**Figure 3-16:  Thermal Response of the TSDE at Heater-Crushed Salt Interface (from Luhrmann and Noseck, 1998).**

Direct measurements of drift closure and crushed salt compaction confirmed this behavior. After the period in which closure results in contact of the drift roof with the crushed salt, the porosity of the crushed salt decreased significantly, and this process was enhanced by heating. For example, starting from an initial porosity value of 0.35 in the center of the drift in the vicinity of the heater decreased to a range from 0.19 to 0.31 on average, with porosity values at the interface of the heater reduced to values as low as 0.135 (Rothfuchs et al., 2003b). Along with this behavior, the permeability in the backfill decreased, and the pressure increased, to a maximum of about 2.9 MPa after five years of heating (Luhrmann and Noseck, 1998), with values as high as 4 MPa measured by the end of the experiment (Rothfuchs et al., 2003). In general, drift closure, and hence backfill compaction and porosity reduction, was slower than predicted by models, but still

very significant. For example, drift closure obtained from convergence measurements at a location within the heated region was 0.31 m. Post-test forensics of the test bed revealed a spatial trend of porosity with increasing porosities from the floor to the roof. Within the zone expected to be disturbed by mining (the EDZ), a pair of boreholes were drilled immediately parallel to the drifts, and permeability measurements were made. All permeability values obtained were very low (on the order of $10^{-22}$ m$^2$), suggesting that any mining-induced fractures had healed during the heating phase, resulting in permeabilities similar to that of the intact, undisturbed salt. Physical examination of cores from these boreholes confirmed this result.

Corrosion samples installed before heating were recovered to examine the durability of metals in the heated zone. In general, both unalloyed and alloyed steels exhibited a high resistance to general and pitting-type corrosion. Compared to laboratory measurements in which samples were immersed in saline water, corrosion rates in the field were very low, presumably due to the small quantities of water present under the operating conditions of the test. This suggests that under normal conditions, as opposed to scenarios that might lead to inundation of the repository, corrosion will be minor.

### Development of Seals for HLW Disposal Boreholes (DEBORA)

This project, conducted in two phases from 1991 to 1999, had as its goal to improve understanding of crushed salt compaction in backfill and seals during borehole emplacement of heat-generating waste in salt (Rothfuchs et al., 2003). In these tests, a heated borehole was monitored for temperature and closure at multiple locations. The porosity of the compacting backfill materials were determined by calculating the volumetric change from the closure measurements, and the permeability of the material was measured periodically from gas flow measurements.

The results of the experiments indicated that the crushed salt backfill behaved differently than material tested in the laboratory. Rothfuchs et al., (2003) observed that in the initial stages of compaction, when the crushed salt porosity in the in situ tests were >0.2, the laboratory conditions used to parameterize the pre-test model predictions were not replicated in the field. Therefore, the model did not closely predict the field data because the inability of the model to represent laboratory data for porosities >0.2 (porosity values of 0.2 or less were used to derive the parameters for the material model). The model more closely predicted the field behavior later in the test, when the compaction reduced the porosity to values of 0.2 or less. This result confirms the importance of obtaining laboratory data at conditions representative of the field conditions to obtain accurate predictive modeling capability. Another result from the DEBORA investigations was the derivation of correlations between permeability and porosity of crushed salt. The correlations exhibited significant particle size dependence.

**Backfill and Material Behavior of Underground Salt Repositories (BAMBUS)**

The Backfill and Material Behavior in Underground Salt Repositories (BAMBUS) project, which can be considered to be the laboratory, modeling, and post-test analysis of the TSDE tests, had as its goal the interpretation of temperature and stress dependent compaction behavior of crushed salt backfill and the surrounding EDZ (Bollingerfehr et al., 2004). The project, a joint effort involving a host of European countries and the Commission of European Communities, comprise the follow-on and ancillary activities used to derive information from the TSDE, including the behavior of backfill, instrument reliability, EDZ investigations, corrosion, and model validation. The project consisted of two phases. The first focused on predictions of field test behavior and the collection of laboratory data and its use in field-scale models. The second phase was designed to further interpret the field test results and refine the models to resolve discrepancies between models and field observations. With respect to the EDZ, in addition to measurements in the TSDE heated area, investigations were conducted in other locations: in a pillar of a mining room in the Asse mine excavated in the 1950's, and in a lined drift constructed in 1914 (Bechthold and Hansen, 2003).

Achieving an improved understanding of the EDZ was a principle aim of the BAMBUS project. Field investigations at the TSDE site, including hydraulic fracturing and physical observations and core recovery, were the primary means for studying EDZ evolution. With regard to the extent of the EDZ, increased permeability was found to depths of about 1.5 m below the floor, and within the first 0.5 m into the walls (Bechthold and Hansen, 2003). Permeability values were about $10^{-15}$ m$^2$, compared to intact, undisturbed salt which were $10^{-21}$ m$^2$ or lower. A complicating factor in interpreting the results forensically was the propensity for cooling fractures to form after termination of the heating. These fractures were not expected to form in a repository setting, and thus were an artifact of testing that must be taken into account (Rothfuchs et al., 2003b). To represent the evolution of EDZ permeability, a power law model was developed in which the permeability at any time is a function of the porosity, as well as the initial values of permeability and porosity in the EDZ (Rothfuchs et al., 2003b). With such an approach, the initial, mining-induced permeability can be represented, along with its gradual reduction due to creep compaction and reduction of porosity. Rothfuchs et al., (2003b) observed that the model did not capture the effects of thermally activated fracture healing that presumably served to reduce the permeability of the EDZ to extremely low values by the end of the test. This deficiency was cited as a motivation for future work to improve the model.

Understanding of the compaction of the crushed salt backfill, previously discussed in the TSDE section above, was another aim of the BAMBUS studies. BAMBUS investigators focused on the collection of laboratory data, acquisition of post-test field samples for observation and further laboratory data collection, and numerical modeling to provide a quantitative description of the field test results. Laboratory investigations of backfill behavior confirmed that the dominant mechanism of compaction was mechanical translation of grains and brittle processes, rather than pressure solution or crystal plasticity (Bechthold and Hansen, 2003). Forensic samples from the TSDE heated area suggested generally that the in situ crushed salt may have exhibited less resistance during

compaction samples tested in the laboratory. Finally, Bechthold and Hansen (2003) pointed to the need to investigate further the consolidation behavior of dry backfill at low porosities, at levels of compaction greater than those experienced in the field test.

With respect to modeling, the BAMBUS studies demonstrated the value of critically testing models against field data in order to improve their predictive capability. The modeling approach used in the BAMBUS project was to benchmark a variety of models against the same data sets to examine the positive and negative attributes of different modeling assumptions. In general, as expected, the thermal response was reproduced most accurately by all models, suggesting that the models for thermal conductivity in the crushed and intact salt regions were well represented (Bechthold and Hansen, 2003). However, two-dimensional models of thermal-mechanical behavior developed in advance of the tests were found to significantly over-predict drift closure and porosity decrease in the backfill. A combination of dimensionality effects (i.e. the inadequacy of two-dimensional models) and boundary effects in the model were found to be the cause of this discrepancy (Rothfuchs et al., 2003b). Subsequently developed three-dimensional models have corrected these problems, and the agreement of model and field data are now significantly improved. According to Bechthold and Hansen (2003), further improvement may lie in the development of improved constitutive models for dry salt reconsolidation.

Finally, instrument performance and corrosion of introduced materials were a focus of BAMBUS. Corrosion was summarized earlier in the TSDE section, so here the lessons learned from the instrument deployment are summarized. During excavation, a variety of gages and sensors were recovered, including temperature, pressure, displacement, and gas sampling probes. Visual inspection indicated physical damage to some instruments caused by creep deformation, but little evidence of corrosion (Bollingerfehr et al., 2004). Further examination and recalibration indicated that in most cases, instruments performed very well even after a decade of use in a harsh environment. Bollingerfehr et al. (2004) concluded that the exercise of dismantling of the test equipment is highly recommended for quality assurance purposes, and further recommended that protection of cabling from the harsh conditions of the test, and/or the development of wireless data transmission systems, be considered in future field campaigns.

### Advective and Diffusive Gas Transport in Rock Salt Formations (ADDIGAS)

The purpose of the ADDIGAS project was to examine issues of the advective and diffusive gas transport in the EDZ not resolved in previous projects such as the TSDE tests. The tests, described in Jockwer and Wieczorek (2008), consisted of gas and liquid injection measurements to determine permeability of the EDZ, an important parameter in terms of the performance of geotechnical barriers such as drift seals. The project focused on the region very close to the drift wall, and included testing of permeability after physically removing the EDZ in a section of the drift. Permeability, including anisotropy, and gas diffusion were measured in a section of the Asse mine at the 800 m level (Figure 3-15). Measurements were also compared to constitutive relations developed and used in previous modeling activities.

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As presented in Jockwer and Wieczorek (2008), the results of gas diffusion experiments indicated that significant gas diffusion takes place in either the EDZ or even the rock tested after cutting off the EDZ, with the latter resulting in a one order of magnitude decrease compared to the EDZ. Diffusion coefficients had the expected dependence on the size of the diffusing gas molecule, and in situ water appeared to have no effect on gas diffusion, presumably because of the low water content of the Asse mine salt. Gas permeability measurements exhibited the expected trend of high permeability immediately adjacent to the floor (of order $10^{-14}$ m$^2$) decreasing to $10^{-17}$ m$^2$ at a depth of just 0.9 m. Removal of 1 m of salt resulted in permeability measurements of $10^{-18}$ m$^2$ near this new surface, decreasing to $10^{-19}$ m$^2$ at a depth of 0.3 m. Subsequent measurements 14 months later indicated that these low permeability values persisted, indicating that the effects of the removal of the EDZ are durable. Both gas and brine injection testing indicated that at the scale of the drift, permeability is anisotropic, with much higher values parallel to the drift than perpendicular to it.

## 3.3.2    SUMMARY AND APPLICABILITY OF DISPOSAL CONCEPT

The testing performed in the domal salt in the Asse mine relates both to waste disposal in canisters emplaced in vertical boreholes in the floor of rooms and the in-drift disposal concept of placing canisters on the drift floor and covering them with crushed salt backfill. The entire suite of tests was performed to better understand the thermal, mechanical, and brine migration behavior of domal salt for wastes that generate significant heat. Gas generation was also studied, along with instrumentation durability through forensic observations and post-test recalibration of equipment deployed in the TSDE heater test. Thus, the suite of tests conducted in the Asse mine provide relevant information for either borehole or in-drift waste emplacement concepts. The data sets generated are useful for informing conceptual models and for validating numerical models based on those conceptual models.

Specifically, the TSDE test is a one-of-a-kind field investigation of the behavior of backfill in drifts for extended time periods in which drift closure and crushed salt compaction occurred. There is no other test conducted to date that approaches the time frame (about a decade) and spatial scale (tens of meters) over which the reconsolidation behavior was observed. Thus, the TSDE and accompanying BAMBUS projects should be considered to be a primary investigation on which future salt disposal concepts and studies are based, especially those in which the consolidation behavior of backfill is a technical objective.

## 3.3.3    RELATIONSHIP TO UNDERGROUND TEST PROGRAMS

With respect to relevance of the studies in the Asse mine to other sites at which test programs may be carried out, the potential similarities to other sites are substantial, given that a variety of tests were conducted under heating conditions of interest for high-level waste disposal. The principle site-specific factor that must be considered when assessing the degree of applicability is the geologic setting. Clearly, relevance of this work is strongest for other domal salt sites, and

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potentially less relevant for bedded salts. Other factors to consider are the presence of other minerals in the halite and the stress regime.

When specifically comparing the Asse mine results to potential bedded salt sites, differences in the water content and the percentage of hydrous minerals in the salt will have a strong bearing on the level of transferability of these results to the behavior of bedded salt. For example, the water content of the Asse salt is 0.04% (Schlich and Jockwer, 1985), compared to values of 0.1 to about 2% in bedded salt at WIPP (Roedder and Belkin, 1979). In comparing the brine liberation results from heated borehole experiments in the WIPP bedded salt to analogous tests in the Asse mine, Nowak and McTigue (1987) observe that the approximately 0.1 kg of water collected after about two years in Asse is far less than the 36 kg and 38 kg of water collected in two comparable WIPP boreholes. Even after accounting for differences in the water content and well radii, the quantity of water produced at WIPP was more than one order of magnitude larger than expected based on simple models. Furthermore, the observation in WIPP bedded salt of an initial flux of water into the hole before any heating was not observed in the Asse borehole, which only produced water upon heating. These differences point to the limited applicability of Asse brine migration results to bedded salt sites. The higher water content and potentially different structure of the pore space through which water percolates toward the borehole are likely reasons for the differences.

In addition, the quantity of water present in the pore space of a potential repository site is likely to influence the fracture healing process and the mechanisms and rate of consolidation of crushed salt in the repository. Therefore, if bedded salt is selected for examination, it will be important to examine these mechanisms at the conditions of that potential repository site, rather than relying on the Asse mine results.

Given those caveats, the decades-long suite of experiments and tests at this site provides a substantial set of information for understanding and validating thermal and mechanical behavior of salt, and provides a proof of concept for measurement systems capable of withstanding the harsh environment of a heated repository in salt. Therefore, the Asse mine experiments should be considered closely in any future proposed underground test program.

## 3.4  GORLEBEN: DOMAL SALT

The German nuclear waste repository program evaluated salt structures throughout the country and chose the Gorleben salt dome in 1977 as a potential repository for further evaluation.  Exploration and testing activities at the site began in 1979 and continued through 2000.  On October 1, 2000, a moratorium was placed on any further investigation or construction activities at Gorleben (BMWI 2008).  All exploration, characterization and experimental activities up to the moratorium are summarized in detail in four reports published by the German Federal Institute for Geosciences and Natural Resources (BGR). Reports 1–3 describe the geological and hydrogeological characterization of the overburden, surrounding country rock, and the salt structure (Klinge et al., 2007; Köthe et al., 2007; Bornemann et al., 2008).  Report 4 describes the in situ and laboratory geotechnical investigations at the site (Bräuer et al., 2011).  The results of all the

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exploration work up to the moratorium argue in favor of the suitability of the salt dome to host a repository (BMWI 2008).

The Gorleben salt dome is located near the town of Gorleben in Lower Saxony, northwest Germany (Figure 3-17). The dome is a northeast-southwest aligned structure approximately 14 km long by 4 km wide. At its shallowest, the top of the salt is found at 250 m below ground surface (bgs). The base of the salt structure is at 3200-3400 m bgs (Bräuer et al., 2011). The salt dome intrudes and deforms Triassic – Quaternary strata (Figure 3-18). Tertiary – Quaternary sediments cover the dome to a maximum depth of 430 m and have clearly been thinned because of salt tectonics.  Uplift rates range from 0.08 mm/yr during the Cretaceous to 0.02 mm/yr during Tertiary and Quaternary time (Klinge et al., 2007; Köthe et al., 2007). Compositionally, the dome is predominantly halite, with lesser amounts of carnallite (hydrated K-Mg chloride), anhydrite and claystone.  In the target exploration zone for the repository (~840 m bgs), the formation is approximately 95% halite and 5% anhydrite. The salt diapirism (salt tectonics), both large and small scale folding has deformed (folded, fractured, boudinaged) anhydrite and claystone beds (Bornemann et al., 2008; Bräuer et al., 2011). These features are of interest in terms of brine and gas occurrences and movement, and their geomechanical properties.
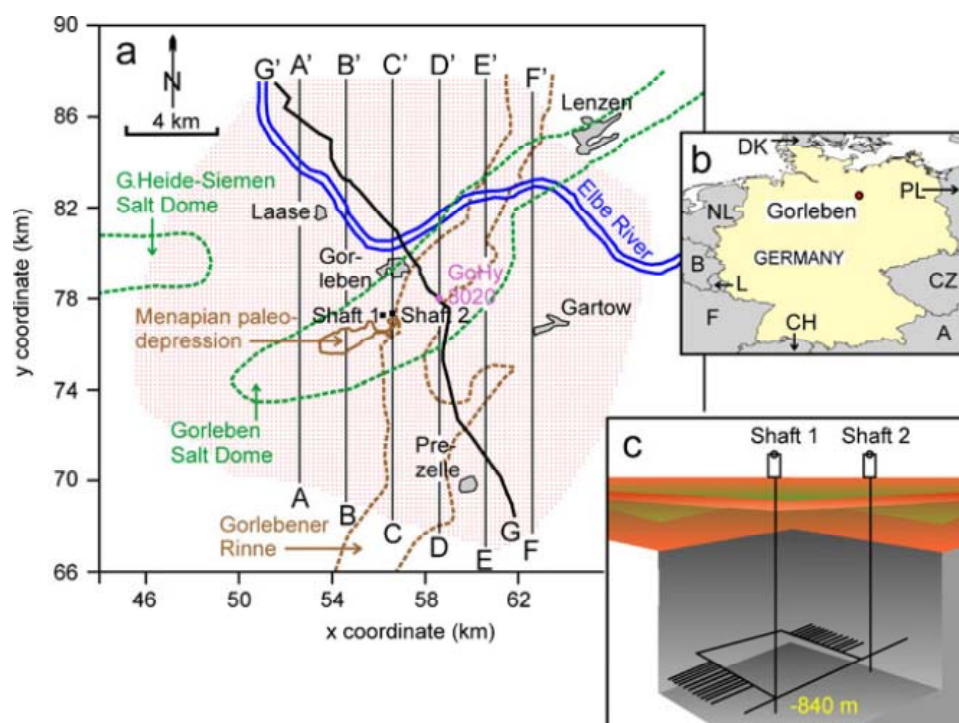


**Figure 3-17:  Location of Gorleben Salt Dome (panels a, b).  Panel C is a Schematic of the Underground Workings (from Schwartz, 2012)**
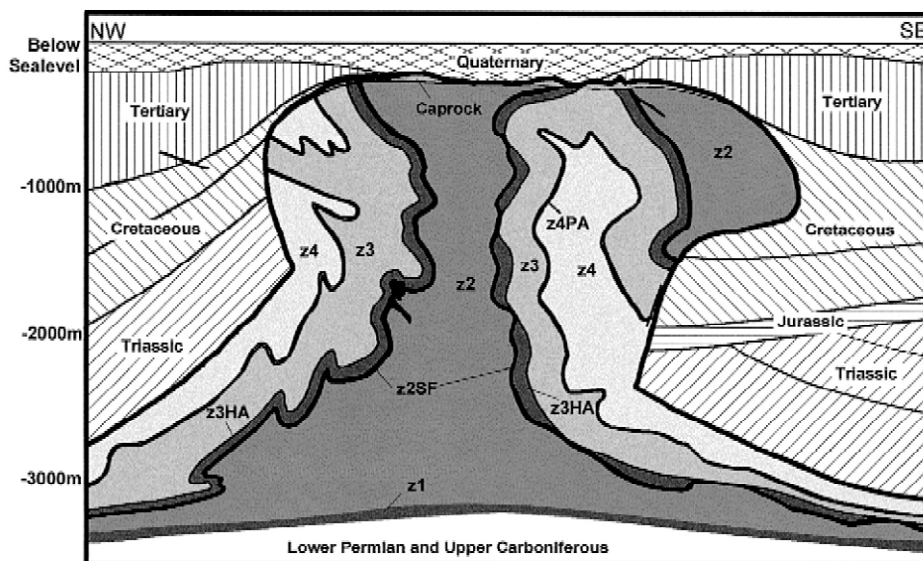
**Figure 3-18: Geologic Cross-Section of Gorleben Salt Dome. The target level for the repository is ~840 m bgs within the central z2 salt. Note the titling of units and significant thinning of Tertiary section due to salt tectonics. (Siemeann and Ellendorf, 2001)**

The Gorleben site was explored for hydrocarbons in the 1930's through 1950's using seismic methods and exploratory drilling. The salt dome has not seen any mining activities before repository investigation activities. The current workings include 2 shafts that are connected by a drift at the 840 m level. Multiple cross-cut drifts, rooms and exploration areas have been constructed at this level for the repository investigations. Mining and construction activities ceased along with investigations in 2000 because of the moratorium (BMWI, 2008).

### 3.4.1    SUMMARY OF INVESTIGATIONS

#### Temperature

Extensive characterization of the ambient temperature field including both the vertical and horizontal temperature gradients, are documented for the Gorleben salt dome. Measurements were made using investigative boreholes and underground measurements made in the drift environment. At the repository target level of 840 m bgs, the ambient temperature averages 38°C which is warmer than predicted by the standard geothermal gradient (Bräuer et al., 2011). Post shaft and drift construction temperature measurements were continued until the moratorium to evaluate the change to the natural temperature field caused by construction and ventilation. Heater tests were not conducted in the Gorleben subsurface environment. The ambient environment tests results from the Asse salt mine were used as the basis for evaluating the salt behavior.

Samples from the exploration level (840 m bgs) were subjected to a suite of laboratory measurements to determine their thermal properties. Thermal conductivity was measured from 0 – 200°C and 0 – 20 MPa. It was found that the thermal conductivity of halite decreases with increasing temperature (5.5 W/(m*K) at 20°C; 3.5 W/(m*K) at 200°C), and increases with increasing

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pressure. At ~5 MPa pressure it was observed that micro-fractures in the halite begin to heal. The thermal expansion for halite was determined by heating at 5 K/minute from 20 – 290°C, resulting in a thermal expansion coefficient of $3.7 \times 10^{-5}$ $K^1$. The specific thermal heat capacity ($c_p$) determined between 20 and 250°C ranged from 0.85 to 0.90 kJ/(kg*K) with a temperature dependence of 0.847 kJ/(kg*°K) + 0.000274 T (°C).

**Geomechanical**

Rock stress and deformation studies were conducted in situ and in the laboratory to determine the mechanical properties of the repository rocks and the response of the materials to mining activities. All of these studies are summarized in detail in Bräuer et al. (2011). The ultimate goal of the studies was to develop thermo-mechanical equations of state for repository safety assessment modeling.

Samples for laboratory measurements were collected using over-coring methods to collect intact samples free from damage induced from drilling. Tests were also conducted on crushed salt (compaction tests). Tests included ultrasonic, Brazilian, triaxial, uniaxial, biaxial, and creep measurements. These tests determined the following list of properties: density, $V_p$, $V_s$, ultrasonic anisotropy, Young's modulus, Poisson ratio, dynamic moduli of elasticity, indirect tensile strength, indirect compressive strength, and stress, strain, and creep behavior.

In situ measurements at the exploration level included borehole hydrofracturing tests using packers and monitoring at long-term stress stations. The monitoring stations were installed to investigate stress and deformation behavior over time to examine changes caused by variations in natural conditions and those imposed by the excavation of drifts and shafts (unloading and ambient temperature changes caused by ventilation).

One region of particular interest was the "Gorleben Bank", which is a deformed horizon of densely bedded anhydrite. This horizon varies in thickness and contains joints and clays and acts as a zone of brine/gas accumulation and migration. Instrumentation was installed to track deformation in this horizon resulting from excavation (e.g., opening of fissures). No opening of fissures was noted during the investigation activities.

**Hydrological**

Hydrological investigations were aimed at determining the permeability of the various salt units, fractured zones, layers of anhydrite and claystone, and to characterize the occurrence of fluids and gases.

Only a limited number of permeability measurements were completed because of the moratorium. Measurements were made in situ using borehole packers and fluid/gas injection. In unfractured halite zones the permeability ranged from $10^{-22}$ to $10^{-20}$ $m^2$. In fractured halite zones sealed with secondary mineralization, the permeability ranged from $10^{-22}$ to $10^{-18}$ $m^2$ (Bräuer et al., 2011).

In general the water content of the salt dome was observed to be ranging between 0.1 and 2% by volume and having porosities ranging from 0 to 1.6%

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(Bornemann et al., 2008). However, brine and gas accumulation occurred within beds and fissures in anhydrite and claystone, fractures sealed with secondary mineralization along halite grain boundaries, and in fluid/gas inclusions (Bornemann et al., 2008; Bräuer et al., 2011). Pockets of fluids found in the displacement joints and fracture zones were generally small, but in rare cases ranged up to volumes of a few cm$^3$. Actual observed flow from an exploration borehole was 166 cubic meters. Salt tectonics and creep isolated most pockets of fluid from the regional groundwater such that they are at lithostatic pressures. The fluids found were considered stable at the current rates of deformation in the dome; although some in-flow was observed into the underground workings Calculations from material balance inflows ranged from 100 to several thousand meters cubed. Compositionally, the naturally occurring fluids found were $MgCl_2$ and $CaCl_2$ brines, with lesser amounts of dissolved sulfates (Bornemann et al., 2008). Fluids introduced during mining activities had different compositions (e.g., NaCl-rich) characteristic of undersaturated waters encountering and dissolving rock salt locally (Bornemann et al., 2008).

Liquid and gaseous hydrocarbons were also found in addition to brines (Bornemann et al., 2008; Siemann and Ellendorf, 2001). They were located in fissure reservoirs in anhydrite and claystone (e.g., the Gorleben Bank), and in fault and fissure zones in secondary halite and carnallite. Gas-rich zones of salt were referred to as "crackling" halite/carnallite in locations where unloading induced by mining caused decrepitation of gas filled inclusions. In addition to hydrocarbons, nitrogen gas were also found in gas occurrences. (Bornemann et al., 2008).

## 3.4.2 SUMMARY AND APPLICABILITY OF DISPOSAL CONCEPT

The proposed disposal concept for the Gorleben repository was a combination of in-drift placement and borehole disposal (Figure 3-19) in domal salt. Self-shielded casks (POLLUX) containing spent fuel were to be placed in drifts and subsequently backfilled with crushed salt. Canisters containing vitrified high-level waste were to be disposed in vertical boreholes drilled from mine drifts. This proposal concept is applicable in terms of drift and borehole placement; however, the waste packaging is a specific German design and the waste forms are specific to the German program. Additionally, the Gorleben site is in domal salt and results of the investigations may not be in all cases applicable to bedded salt.
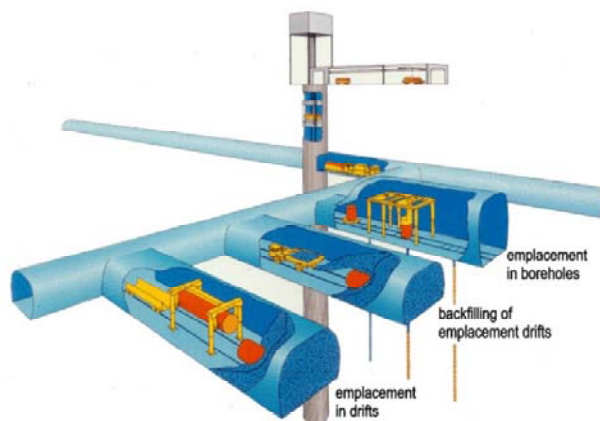
**Figure 3-19:  Disposal Concept Including Drifts & Boreholes (from Biurrum et al., 2010).**

### 3.4.3    RELATIONSHIP TO UNDERGROUND TEST PROGRAMS

Studies at the Gorleben salt dome are useful for study design ideas and comparative purposes with the test programs at WIPP in terms of geomechanical and hydrological testing techniques.  However, the results from Gorleben are most applicable to other domal salt sites and not necessarily the bedded salt in the Delaware basin.  Also, although the in-drift disposal concept is similar, heater tests were not conducted in the mine environment at Gorleben.    All thermomechanical properties were measured in the laboratory on extracted samples.

Although both German and U.S. salt domes were formed by diapirism, the resultant structures generally are very different.  In general, U.S. salt domes are more mineralogically homogeneous and less structurally contorted than their German counterparts.  In many respects, the German salt domes are more like bedded salt deposits in the U.S. that have been deformed by tectonic action.

## 3.5  MORSLEBEN: DOMAL SALT

The repository for radioactive waste Morsleben (Endlager für radioaktive Abfälle Morsleben-ERAM) is a deep geological repository for radioactive waste in the rock salt mine Bartensleben in Morsleben, district Börde in the federal state Saxony-Anhalt in North-West Germany (Figure 3-20). The ERAM is located in the River Aller Area, about 135 m above sea level. The former potash and salt mine consists of two shafts, Bartensleben and Marie, and a mine system that stretches 5.6 km northwest to southeast and 1.4 km west to east. The sinking of shaft Marie began 1897. The sinking of shaft Bartensleben took place from 1910 to 1912. The respective mine openings are connected at several places.
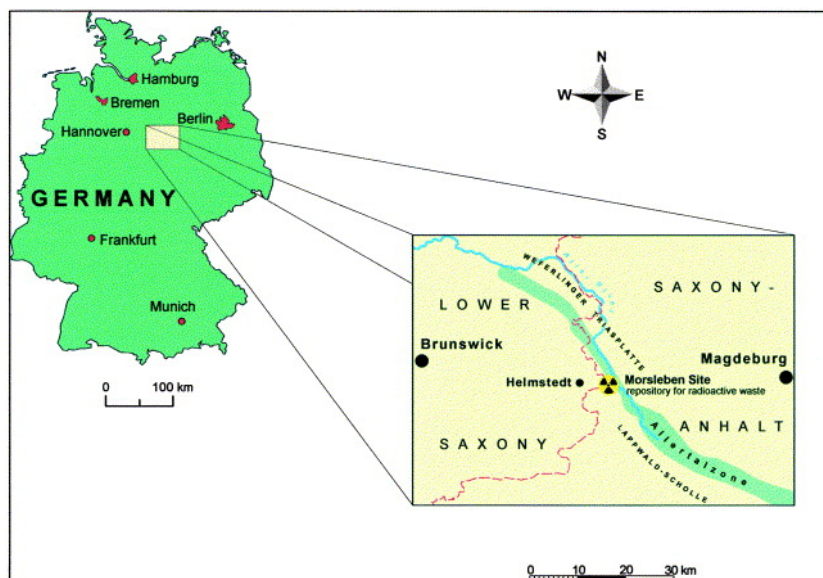
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**Figure 3-20:  Location of Morsleben Site (From Behlau et al., 2001).**

In 1970, in the German Democratic Republic, the ERAM was selected to serve as a repository for low- and intermediate-level radioactive waste with negligible heat generation. Following studies and the successful demonstration of the disposal technologies used, the operational license was granted in 1981. Subsequent to the German reunification on October 3rd, 1990, the Federal Government of Germany took over the responsibility and the facility obtained the status of a federal repository. The disposal of waste was terminated on September 28th, 1998. Now the repository is under licensing for closure. A closure concept has been established, which is based on a comprehensive backfilling of the excavations with a hydraulically transported salt concrete. The function of the backfill is to stabilize cavities as well as to reduce the mine's opening volume and to seal single cavities or groups of cavities containing radioactive waste (Hund et al., 2004).

Radioactive waste was stored from 1971 to 1998 at a depth of about 500 m below ground (Koch, 2006). The two shafts provide access to a widespread system of drifts, cavities, and blind shafts between 320 m and 630 m bgs. The overall volume of the cavities amounts to more than 8 million m³, of which more than 2 million m³ has been backfilled mainly using crushed salt. Some of the caverns have dimensions up to 100 m in length, in a few cases up to 200 m, and 30 m width and height (Hund et al., 2004). Caverns of this magnitude pose a challenge for closure (Figure 3-20). During the operational period of the repository about 36,800 m$^3$ of radioactive waste had been stored (Eilers et al., 2003) with an inventory of about 0.12 PBq (3.2x10$^3$ Ci) (Hund et al., 2004), although other sources cite inventories as high as 0.45 PBq (1.2x10$^4$ Ci) (Ranft and Wollrath, 2002).

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**Figure 3-21:  Photos of ERAM Caverns with Waste (from Google Earth)**

The ERAM is located in the structure of the "Allertalzone", named after the small river Aller, covering an area of about 50 km². Tectonically it is a fault structure caused by extension tectonics, which separate the Lappwald block and the Weferlinger Triassic block. In the fault zone, Permian evaporate strata intruded and accumulated to form a salt plug, the now existing salt structure (Figure 3-22). The top of the salt leaching surface is at 140 m below mean sea level and the thickness of the salt body varies between 380 m and 500 m (Kreienmeyer et al., 2004). The salt body is characterized by an intensive folding of the layers and a high amount of anhydrite rocks. The stiff anhydrite layers, broken into blocks during the flow of the plastic salt strata, stabilize the internal salt structure excavations. Another feature of the deposit is the occurrence of potash seams. The salt leaching surface forms a flat plane at a depth of approximately 140 m below mean sea level. The overlying cap rock has a very low hydraulic conductivity and isolates the salt structure from the aquifer system in the overlying upper Cretaceous rocks. The aquifer is overlain by unconsolidated or semi-consolidated glacial sediments. In addition, the surface cover is provided mostly by Quaternary sediments.

Active brine inflows into the mine openings have been observed. One brine seep location is situated far from the disposal areas in the Marie mine (potash seam H) and has an inflow rate of about 10 m³/year. A second brine seep with an inflow rate of about 1 m³/year is located on the first level of the central part in the Bartensleben mine. The chemical composition of the NaCl-saturated, Mg-rich solutions have been nearly constant and prove contact exists with potash salts (Eilers et al., 2003).

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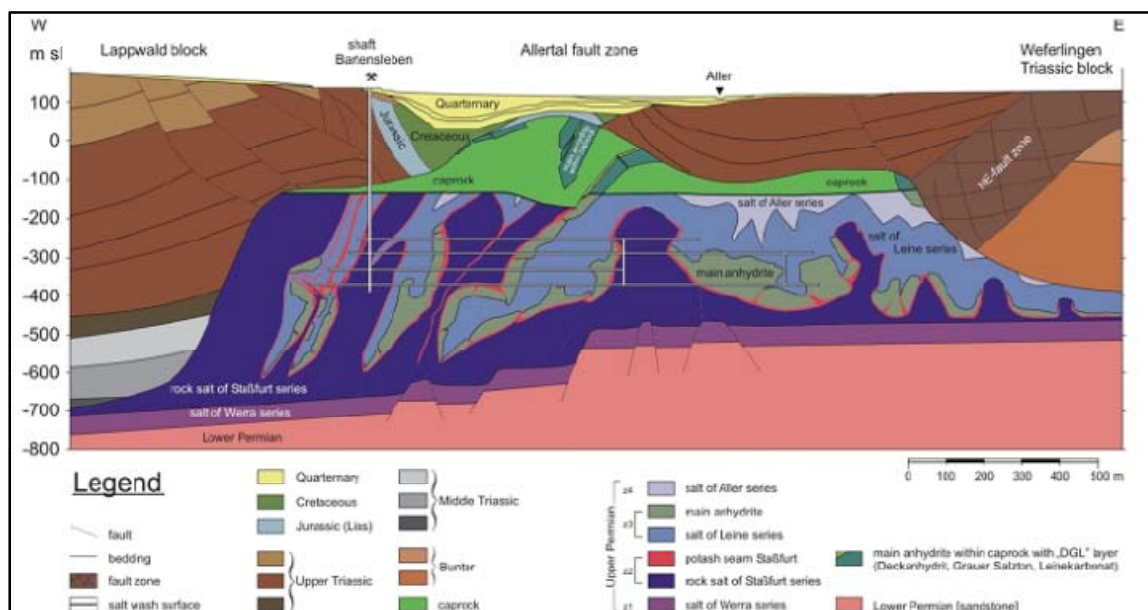


**Figure 3-22:  Cross Section of Local Geology of ERAM. (From Brewitz et al., 2008).**

## 3.5.1  SUMMARY OF INVESTIGATIONS

### Stabilization Measures

To reduce the radiological consequences of a brine intrusion scenario, the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) investigated several concepts for effective backfilling and sealing. Material selection and—in view of the specific geological situation—adequate positioning of sealing systems underground contribute substantially to the long-term safety of the repository (Brewitz et al., 2008).

In November 2001, a significant roof fall occurred in a cavity on the 297 m NN level of the mine, which was a restricted area because of the danger of roof falls (Figure 3-23). Numerical calculations, geotechnical surveillance measures, and in situ observations show that the risk of a progressive failure in the central part of the Morsleben repository affecting repository safety cannot be excluded. To analyze the geomechanical situation, numerical calculations (using FLAC3D) and site investigations by ground penetrating radar and hydraulic fracturing were performed, in addition the exploratory programs were designed to describe the geological and geomechanical situation (Kreienmeyer et al., 2004).

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**Figure 3-23:  Photo Showing Rock Fall of November 2001 (from Herklotz, 2009).**

A closure concept has been established which is based on a comprehensive backfilling of the excavations with a hydraulically transported salt concrete. The function of the backfill is to stabilize cavities as well as to reduce the mine´s open volume and to seal single cavities or groups of cavities containing radioactive waste. Stabilization measures are necessary to protect the ground surface and to avoid the evolution of pathways induced by mechanical failure of the rock salt barrier around the disposal areas (Eilers et al., 2003). Photos of some backfilled caverns are shown in Figure 3-24
(from http://en.wikipedia.org/wiki/Morsleben_radioactive_waste_repository).



**Figure 3-24:  Photos Showing Cavern Closure Techniques at Morsleben.**

## Effects of Hydration Heat

Herklotz (2009) describes results from load cell calculations of measured stresses in the first filled cavern that show very high values (about 5 MPa). Thermal expansion during hydration of concrete and geometric factors were posed as possible reasons for the high measured pressures, but final explanations were not proposed. Herrlotz (2009) also presented temperature

data from the first backfilled cavern. Temperatures reached a maximum of about 54°C at about 40 days after backfilling, which was in good agreement with calculated (modeled) temperatures (Herlotz, 2009). Additionally, it was observed that permeability may increase caused by crack evolution resulting from hydration heat during the construction phase or by mechanical loads (Eilers et al., 2003).

### 3.5.2     SUMMARY AND APPLICABILITY OF DISPOSAL CONCEPT

The disposal concept for the ERAM repository at Morsleben was in-drift placement disposal in domal salt. Waste forms were to be placed in drifts and backfilled with crushed, run of mill salt, as well as salt concrete. This proposal concept is applicable in terms of in-drift placement. However, this is a repository in domal salt and results of the investigations may not be applicable to bedded salt in all cases.

### 3.5.3     RELATIONSHIP TO UNDERGROUND TEST PROGRAMS

Studies at the ERAM repository at Morsleben are useful for study design ideas and comparative purposes with the test programs at WIPP in terms of lessons learned from stabilization and closure practices. However, the results from Morsleben are probably most applicable to other domal salt sites and not necessarily the bedded salt in the Delaware basin. Although the in-drift disposal concept is similar, heater tests were not conducted in the mine environment at Morsleben. Observations of elevated pressures and increased permeabilities as a result of hydration heat from concrete provide important information on the use of these stabilization materials.

## 3.6   PALO DURO BASIN (DEAF SMITH COUNTY)

The Deaf Smith, Texas site was a potential civilian high-level waste site located in geologic salt deposits in the Palo Duro basin in northern Texas. The site was one of three potential high-level radioactive waste disposal sites that the DOE was analyzing as directed by Congress (U.S. Congress 1987; DOE, 1988b). The goal was to derive site characterization information from the site and develop a conceptual repository design such that an Environmental Impact Statement could be developed. Most of the historical information relating to this site consists of planning documents because of the timing of this investigation – a Congressional act in 1987 removed this site from the list for further consideration. Lomenick (1996) summarizes the characterization efforts and regulatory milestones associated with Deaf Smith in Appendix K of the summary. Reconnaissance activities included work about the lithology, thickness/depth, distribution, structural geology, and dissolution behavior for the evaporite sequence of the site (Johnson, 1976.)

A draft Deaf Smith site characterization plan (SCP) was completed for the site in January 1988 (DOE, 1988a: Volumes 1-10), but no Environmental Impact Statement or significant site-specific characterization work was actually completed.

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# 4.   CONCLUSIONS

The test configurations and geologic settings of the salt testing programs conducted outside the Delaware Basin are documented in this report.  In summary, each testing program had a unique disposal concept and resulting thermal testing configuration including placing heaters in the floor of the emplacement room (e.g., Project Salt Vault, Avery Island, WIPP) or placing heater canisters lengthwise in a drift covered with salt (e.g., the TSDE and BAMBUS tests in the Asse Mine).  The testing conducted at Lyons was in bedded salt; whereas, the testing at Avery Island, the Asse mine, Gorleben, and Morsleben were conducted in salt domes. Some of the testing programs (e.g., brine migration experiments at PSV, Avery Island and the Asse Mine in Germany) explicitly examined the migration of synthetic and natural brines in a temperature field produced by the electrical heaters. Table 4-1 below summarizes the thermal testing that has been conducted previously, both in the U.S. and internationally.

| Site | Emplacement Concept | | Geology | Thermal Characteristics of Tests[1] |
|---|---|---|---|---|
| | **Borehole** | **In-drift** | | |
| Lyons, Kansas (Project Salt Vault) | X | | Bedded salt | • Peak salt T ~200°C <br> • 2 year heating duration <br> • Power – 10.4 kW/heater |
| Avery Island | X | | Salt dome | • Peak salt T ~160°C <br> • ~3 year heating duration <br> • Power – 3-6 kW/heater |
| Asse | X | X | Salt dome | • Peak salt T ~210°C <br> • 10 year heating duration <br> • Power – 6.4 kW/heater |
| Gorleben | X | X | Salt dome | • N/A |
| Morsleben | | X | Salt dome | • N/A |
| WIPP (historical) | X | | Bedded salt | • Power – 64 kW total power between 3 rooms and 59kW in a single room |
| **WIPP – Proposed Testing Program** | | | | |
| SDDI | | X | Bedded salt | • Peak salt T ~80-150°C <br> • 1-2 year heating duration <br> • Power – 0.5-2 kW/heater |
| SDI | | X | Bedded salt | • Peak salt T >200°C <br> • 4 year heating/cooling duration <br> • Power – 8.5 kW/heater |

1. Multiple heater tests were conducted at most sites.  This column describes the tests most applicable to the SDI/SDDI testing concepts.

**Table 4-1: Summary of Historic and Proposed Salt Thermal Testing**

The thermal test configurations of past experiments conducted at WIPP were largely based on the premise of waste emplacement in vertical boreholes drilled into the salt beneath the repository drifts. Over a decade's worth of operational experience at WIPP suggests that this disposal concept, if implemented for heat-generating waste, could lead to many repository

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operational limitations and waste containerization restrictions (e.g. Nelson and Buschman, 2012). Past work (Bradshaw and McClain, 1971; Jenks, 1979; Coyle et al., 1987; Krause, 1983; Luhrmann and Noseck, 1998; Rothfuchs et al. 2003) has also suggested that the vertical borehole configuration exacerbates local pressure gradients and results in high brine inflow volumes around the hot waste packages, a potentially unwelcome condition that might be avoided by using the in-drift emplacement design as described in *A Conceptual Plan for Salt Defense Disposal Investigations for the Disposal of DOE-EM Managed Wastes* (DOE, 2012). A key focus of future testing programs would be to develop and deploy instruments that track water and water vapor movement to validate these assumptions. Given the potential importance of water fate and transport to repository performance, and the need to provide evidence of a firm understanding of these processes, the present study focused particularly on available field evidence that would provide knowledge and guidance in the design of future field tests.

Based on a review of the information presented in this report, there is a continued need for research into the potential performance of a repository for heat-generating waste in bedded salt and a need to better understand the integrated response of the salt at the field scale, in particular the evolution of the small but non-negligible quantities of water within the salt as the heat from radioactive decay diffuses into the surrounding geologic medium. This conclusion is made even though past field heater tests conducted outside the Delaware Basin and at WIPP have significantly advanced our state of knowledge of salt behavior. However, the combination of test configurations (e.g., borehole emplacement, in-drift emplacement) and/or geologic settings (e.g., domal salt, bedded salt) of the experiments limit the applicability of the test results for direct comparison or as a demonstration of an in-drift disposal concept in bedded salt outlined by the DOE (2012). Table 4-1 illustrates that there have not been any direct thermal tests conducted with an in-drift emplacement arrangement in bedded salt, the configuration and geologic setting outlined in the SDDI conceptual plan. A successful field campaign at intermediate heat loads, targeting the DHLW inventory, is the appropriate next step in the development of the scientific basis for a DHLW repository in salt. If successful, this test would be an important step towards an investigation that defines the limits of acceptable heat loads in a salt repository through the application of even higher heat loads representative of SNF.

This recommendation to investigate salt as a disposal medium, starting with DHLW, follows directly from the wealth of scientific information and operational experience in salt. The successful licensing, recertification, and more than a decade of safe, efficient operations of the TRU waste repository in bedded salt at WIPP is strong testimony to the fact that a repository for long-lived radioactive waste in salt is viable in the U.S. Furthermore, even though scientific questions remain (primarily surrounding the liberation and fate of water under thermal conditions), there is a knowledge base to build upon regarding thermal effects in salt, derived from field investigations in Lyons, Kansas, the Asse salt mine and other locations in Germany, domal salt in the Avery Island salt mine in Louisiana, and at WIPP. A definitive field study on the suitability of bedded salt as a disposal medium, performed underground in a controlled and cost effective manner at the only permitted salt repository in the nation, will move the country forward in its repository quest. There is sound scientific basis to believe that the introduction of heat may actually benefit certain aspects of repository performance, as higher temperatures are expected to enhance removal of accessible brine from the disposal system during emplacement operations and pre-closure. Demonstration of the in-drift disposal concept, first at intermediate heat loads and perhaps later at higher heat loads representative of SNF, would provide confidence to stakeholders, regulators, and policy makers that salt is a fully efficient medium for these heat-generating wastes.

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Motivating this research program (centered on an in-drift disposal and testing concept) is the underlying hypothesis that heat-generating waste may actually be advantageous to permanent disposal in salt, regardless of the transport and fate of brine in a bedded salt repository. Note that an ultimate licensing case for a repository in salt does not necessarily require this hypothesis to be true: it is possible that water may produce minimal effects that have little bearing on a safety case. But from a science perspective, it is important to achieve a firm understanding of the prevailing hydrologic and chemical effects during a demonstration of an emplacement concept to provide the basis for a decision regarding disposal of heat-generating wastes. Operationally focused, coupled thermal-mechanical-hydrologic-chemical (TMHC) field-scale studies and demonstrations, in addition to laboratory-scale studies and computer-generated models, provide the scientific and engineering base of information necessary to build the confidence necessary for legislators, regulators, or public stakeholders to make informed decisions. The field investigations summarized in the present study, along with thermal tests at WIPP, are an invaluable source of information that can be built upon to design these tests.

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